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Simulation and evaluation of routing protocols for Mobile Ad Hoc Networks (MANETs)

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THESIS

SIMULATION AND EVALUATION OF ROUTING PROTOCOLS FOR MOBILE AD HOC NETWORKS (MANETs)

by

Georgios Kioumourtzis

September 2005

Thesis Co-Advisors:	Gilbert M. Lundy Rex Buddenberg

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Mobile Ad hoc networks (MANETs) are of much interest to both the research community and the military because of the potential to establish a communication network in any situation that involves emergencies. Examples are search-and-rescue operations, military deployment in hostile environment, and several types of police operations.

One critical open issue is how to route messages considering the characteristics of these networks. The nodes act as routers in an environment without a fixed infrastructure, the nodes are mobile, the wireless medium has its own limitations compared to wired networks, and existing routing protocols cannot be employed at least without modifications.

Over the last few years, a number of routing protocols have been proposed and enhanced to solve routing in MANETs. It is not clear how those different protocols perform under different environments. One protocol may be the best in one network configuration but the worst in another. This thesis describes a study of those protocols that are best from a DoD perspective. These wireless mobile networks were simulated under different mobility and traffic scenarios to evaluate their performance. The results showed which protocols performed better under several relevant scenarios and exposed a number of design flaws.

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SIMULATION AND EVALUATION OF ROUTING PROTOCOLS FOR MOBILE AD HOC NETWORKS (MANETs)

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This thesis would not have been possible to materialize without the support of my beloved wife and our two daughters Maria and Kleio.

I would like to express my sincere thanks to my two thesis advisors Professor Gilbert Lundy and Professor Rex Buddenberg for their advice, support and encouragement.

I. INTRODUCTION

A. DEFINITION OF MOBILE AD HOC NETWORKS

Over the last few years, wireless computer networks have evoked great interest from the public. Universities, companies, armed forces, and governmental and non-governmental organizations and agencies are now using this new technology.

We can generally classify wireless networks into two categories:

1) Wireless networks with fixed and wired gateways, and 2) wireless networks that can be set up in an “ad hoc” fashion, without the existence of fixed Access Point (AP) and where all nodes in the network behave as routers and take part in the discovery and maintenance of routes to other nodes in the network.

A Mobile Ad Hoc Network (MANET) is a wireless network in which all nodes can freely and arbitrary move in any direction with any velocity. Routing takes place without the existence of fixed infrastructure. The network can scale from tens to thousands of nodes in an ad hoc fashion, providing the nodes are willing to take part in the route discovery and maintenance process.

B. APPLICABILITY OF MANETS

We can broadly define two main areas where MANET technology can be applied. The first area extends the current wired and wireless networks by adding new mobile nodes that use MANET technology at the edge of the network. These could be, for example, drivers in a city who can communicate with each other while obtaining traffic information, students on a university campus, company employees in a meeting room, and many other similar situations. Perhaps one day MANETs, will replace the existing wireless telephony if every user is willing to store and forward data packets with his wireless device.

The second area where MANET technology can be applied is where a communication network is needed, but there is no infrastructure available, or the pre-existing infrastructure has been destroyed by a disaster or a war. MANETs can be used in any situation that involves an emergency, such as search-and-rescue operations, military deployment in a hostile environment, police departments, and many others. In addition, the lack of a wired infrastructure reduces the cost of establishing such a network and makes MANETs a very attractive technology.

C. OPEN ISSUES IN MANETS

There are still many open issues concerning MANETs. They involve efficient routing due to frequent changes in the network topology over time, and security, because each node in the network operates also as a router that stores and forwards data packet from other nodes. Energy consumption is another open issue as nodes in the network transmit not only its data but also data from other nodes. Finally, lower data rates due to the limitation of the physical layer as compared to wired networks.

D. OBJECTIVES AND SCOPE OF THIS THESIS

Over the last few years, many routing protocols for Mobile Ad-hoc Networks have been proposed and enhanced to efficiently route data packets between two nodes in a network. It is not clear, however, how different protocols behave in different environments. A protocol may be the best, one to use in one network topology and mobility scenario, but the worst to use in another. In addition, a tactical mobile wireless network has different characteristics than the same mobile wireless network designed to satisfy commercial needs. A simple example is the network mobility model. Commercial ad-hoc networks are to some extent “chaotic”, in the sense that each node may arbitrarily choose its own velocity and direction. In a tactical environment, the mobility model depends on the type of operation, the size of the deployed unit, the terrain, and other factors that staff officers take into account when planning such operations. In addition, nodes move in predefined directions with predefined velocities and operate as organized groups, again depending, on the type of the operation.

The objectives of this thesis are to 1) find the routing protocols among those that have received close attention from the research community that can satisfy a DoD perspective, 2) to analyze and test those routing protocols under the same network parameters and mobility scenarios, and 3) to evaluate each one based on its performance.

E. THESIS OUTLINE

In the second chapter, we will study and decide which of the proposed and most "popular" routing protocols for mobile ad-hoc wireless networks may be suitable for use in a tactical environment. The network size, mobility pattern, network density, network topology, user traffic, operational environment, energy consumption and other parameters in tactical networks are different from those in commercial networks. The decision of how suitable a routing protocol is for a tactical network will be based both qualitative and quantitative metrics in accordance with [RFC 2501]. In this chapter, our evaluation of the candidate protocols will be based on qualitative metrics.

In the third chapter, we will examine the performance of the routing protocols chosen in the chapter two. The performance analysis of these protocols will be done using simulation software. We will run several simulation scenarios, taking into account the mobility model of the network, the network density, and the user traffic. We will insist on a more realistic mobility scenario to reflect troop movements in which nodes form various clusters independently move across the simulation area. As for the simulation software, we will use the ns2 in a Linux platform, as this software has been used in several citations related to this thesis's simulation experiments, and thus, we can have comparable results.

In the fourth chapter, we will present the results from chapter three and evaluate the performance of each tested protocol, based on the simulation results that represent the quantitative metrics of the tested protocols.

Finally, in the fifth chapter we will suggest which routing protocol is most suitable in a given simulation scenario.

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II. PROPOSED ROUTING PROTOCOLS FOR MANET

A. PROTOCOLS OVERVIEW

1. Performance and Evaluation Issues of Routing Protocols

The Internet Engineering Task Force MANET working group suggests two different types of metrics for evaluating the performance of routing protocols of MANETs [RFC 2501]. In accordance with RFC 2501, routing protocols should be evaluated in terms of both qualitative metrics and quantitative metrics. Qualitative metrics include:

Loop Freedom: This refers mainly, but not only, to all protocols that calculate routing information based on the Bellman-Ford algorithm. In a wireless environment with limited bandwidth, interference from neighboring nodes' transmissions and a high probability of packet collisions, it is essential to prevent a packet from "looping" in the network and thus consuming both processing time and bandwidth.

On-Demand Routing Behavior: Due to bandwidth limitations in the wireless network, on-demand, or reactive-based, routing minimizes the dissemination of control packets in the network, increases the available bandwidth for user data, and conserves the energy resources of the mobile nodes. Reactive routing protocols introduce a medium to high latency.

Proactive Behavior: Proactive behavior is preferable when low latency is the main concern and where bandwidth and energy resources permit such behavior. Mobile nodes in vehicular platforms do not face energy limitations.

Security: The wireless environments, along with the nature of the routing protocols in MANETs, which require each node to participate actively in the routing process, introduce many security vulnerabilities. Therefore, routing protocols should efficiently support security mechanisms to address these vulnerabilities.

Unidirectional Link Support: Nodes in the wireless environment may be able to communicate only through unidirectional links. It is preferable that routing protocols be able to support both unidirectional and bidirectional links.

Sleep mode: In general, nodes in a MANET use batteries for their energy source. The protocol should be able to operate, even though some nodes are in “sleep mode” for short periods, without any adverse consequences in the protocol’s performance.

We will extend the qualitative metrics described in [RFC 2501] by adding **multicasting routing** as an important attribute of a routing protocol, because multicasting, especially in tactical communications, will be broadly used.

In conclusion, a routing protocol for MANETs should keep a balance between latency and routing overhead, energy consumption, and node participation in the routing process, and should employ security mechanisms. For tactical communications, low latency and high packet delivery ratio is more important than low routing overhead. Energy consumption is not always an issue in tactical communications, as nodes may well be suited in vehicular platforms with unlimited energy resources. However, for portable man-pack radio devices, energy consumption is an important issue. In tactical communications, user data will be destined, in many cases, to a group of other users in the network, making multicasting an important attribute of the routing protocol in those networks.

Although, it is not within the scope of this thesis to study the security issues of the routing protocols, we will point out the main security vulnerabilities introduced by the proposed protocols. What we are interested in the security properties of a routing protocol is its ability to function properly even in the presence of internal or external attacks. By saying internal attacks, we mean any directed attack to wireless network form malicious outsiders while internal is the attack directed from malicious insiders. Routing protocols that employ nodes with “special” tasks are more vulnerable than those in which all nodes share the same tasks. A routing protocol should be able to recover from any problem in a finite time without crashing the network. A routing protocol should be able to perform its tasks even though some of the nodes in the network transmit false link state and routing control messages. Other known attacks in wireless communications at the physical layer, are out of the scope of this Thesis.

Quantitative metrics broadly include:

End-to-end data throughput and delay: Many metrics can be used to measure the effectiveness of the routing protocol. Design flaws that increase delay and minimize data throughput can be revealed by these metrics.

Route Acquisition Time: How much time does a protocol need for a route discovery? This is a main concern in reactive routing protocols, as the longer the time is the higher the latency is in the network.

Out-of-order delivery: The percentage of packets that are delivered out-of-order will affect the performance of higher layer protocols such as TCP, which prefers in-order data delivery of packets.

Efficiency: Additional metrics can be used to measure the efficiency of the protocol. One can use them to measure the portion of the available bandwidth that is used by the protocol for route discovery and maintenance. Another measurement calculates the data packet delivery ratio over the total number of packets transmitted and the energy consumption of the protocol for performing its task.

All the above quantitative metrics should be based on the same network attributes, such as mobility, network density, data density, bandwidth, energy resources, transmission and receiving power, antenna types and any other “component” that a simulation tool could provide.

Our performance evaluation of the routing protocols will be based on the above quantitative metrics, which will be defined more precisely in chapter 3.

2. Classification of Routing Protocols

Routing protocols for MANETs can be broadly classified into three main categories:

Proactive routing protocols: Every node in the network has one or more routes to any possible destination in its routing table at any given time. When data received from the upper transport Layer is immediately transmitted to Layer 2, as at least one route to the destination is already in the node’s routing table. Proactive protocols present low latency, but medium to high routing overhead, as the nodes periodically exchange control messages and routing-table information in order to keep up-to-date routes to any active node in the network. However, a node, wasting process recourses and bandwidth, may never use some of these routes. Proactive protocols can also address better security vulnerabilities, because of the periodic exchange of control messages and routing-table information. Thus, a loss or modification of any route update can be overcome by the next scheduled update.

Reactive routing protocols: Every node in the network obtains a route to a destination on a demand fashion. When the upper transport Layer has data to send, the protocol initiates a route discovery process, if such a route does not already exist, to find a path to the destination. Reactive protocols do not maintain up-to-date routes to any destination in the network and do not generally exchange any periodic control messages. Thus, they present low routing overhead, but high latency as compared to proactive protocols. Reactive protocols are more vulnerable to security attacks, as any loss or modification of route discovery and maintenance messages may have severe consequences for network performance.

Hybrid routing protocols: Every node acts reactively in the region close to its proximity and proactively outside of that region, or zone. Hybrid protocols take advantage of both reactive and proactive protocols, but may require additional hardware, such as GPS, separated or integrated into the communication device.

In the next sections we will go through the most promising routing protocols in the above three categories that may be suited to tactical environments.

B. PROACTIVE ROUTING PROTOCOLS

1. Optimized Link State Routing (OLSR)

a. Protocol Overview

Optimized Link State Routing [RFC 3626] is based on the link state algorithm and has been modified and optimized to efficiently operate MANET routing. The main concept of the protocol is to adapt the changes of the network without creating control messages overhead due to the protocol flooding nature. Thus, the designers of OSLR decided to have only a subset of the nodes, named Multipoint Relays (MPRs), in the network responsible for broadcasting control messages and generating link state information. A second optimization is that every MPR may choose to broadcast link state information only between itself and the nodes that have selected it as an MPR.

Optimized Link State Routing is also designed to combine two separate sets of functions. The core set of functions consists of all the protocol functions in play when the protocol operates in a pure MANET, running OLSR as the Layer 3 protocol. A second set of functions provides the additional necessary functions when a node has more than one network's devices and participates in more than one routing domain.

b. Multipoint Relay Nodes

In OSLR, only multipoint relays (MPR) are designated for link state updates and packet forwarding. In a typical flooding-based approach, a node broadcasts a message either if it is the originator or if it has not received this message before. Thus, the number of messages transmitted in the network is almost as large as the number of the nodes in the network. Figure 1a shows a typical flooding scenario. Figure 1b shows the flooding in the entire network when using MPRs.

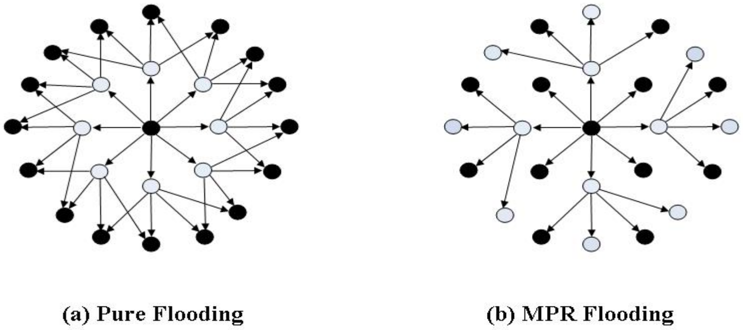


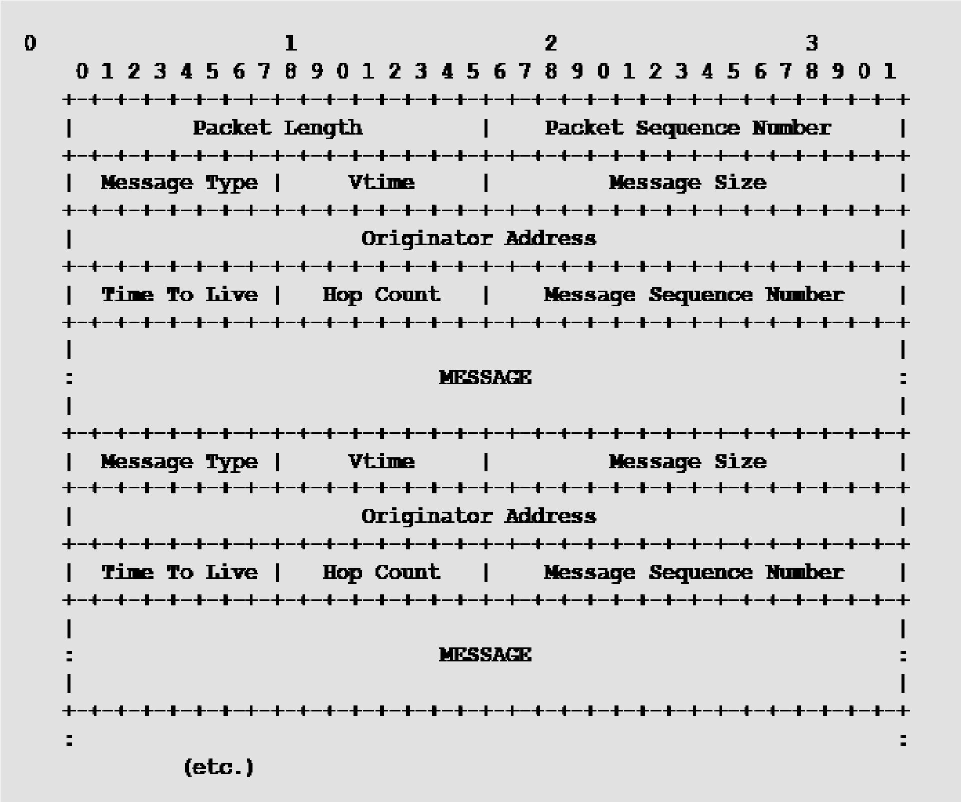
Figure 1. Pure flooding and MPR flooding

As we can see in Figure 1b, only the MPRs, the grey-colored nodes, broadcast messages in the network. It is clear that the number of broadcasted messages can be greatly reduced by the MPRs' implementation.

Although the optimal number of MPRs for a node reflects a smaller number of broadcasting messages in the network, MPR selection is based only on a heuristic that is proposed in [RFC 3626]. The set that consists of the nodes that are multipoint Relays is called *MPR set.* Each node N in the network selects an MPR set that processes and forwards every link state packet that node N originates. The neighboring nodes of N that are not in the MPR set process this packet but do not further broadcast it. A node N also maintains a subset of neighbors, named *MPR selectors,* which is the set of the neighbors that have selected N as one of their MPRs. Each node may have one or more MPRs. A condition for the selection of an MPR node is the assurance of bidirectional links between it and its selectors.

c. Packet and Messages Format

OLSR provides each node with one or more OLSR interfaces (an OLSR interface is a network device participating in a MANET running OLSR). This is achieved by the design and implementation of a unified packet format in which each packet consists of one or more different types of messages. All the messages in a packet share a common header, so nodes are able to retransmit messages of an unknown type. OSLR uses User Datagram Protocol (UDP) as a transport-layer protocol for packet transmission in Port 698. Figure 2 shows the packet format of OLSR.



```
0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |         Packet Length         |    Packet Sequence Number     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Message Type |     Vtime     |         Message Size          |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                      Originator Address                       |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Time To Live |   Hop Count   |    Message Sequence Number    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
 :                            MESSAGE                            :
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Message Type |     Vtime     |         Message Size          |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                      Originator Address                       |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |  Time To Live |   Hop Count   |    Message Sequence Number    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
 :                            MESSAGE                            :
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 :                                                               :
          (etc.)
```

Figure 2. OLSR Packet Format [RFC 3626]

Packet Length: is the length (in bytes) of the packet.

Packet Sequence Number: is incremented by one each time a new OLSR packet is transmitted.

Message Type: indicates the type of message that is the "MESSAGE" part.

Vtime: indicates the length of time after reception, that a node has to consider valid the information obtained in the message.

Message Size: is the size of the message in bytes.

Originator Address: is the main address of the node that sent the message. A node may have multiple interfaces with only one address for every interface. However, each node must define a unique “main” address among the set of addresses that the node has.

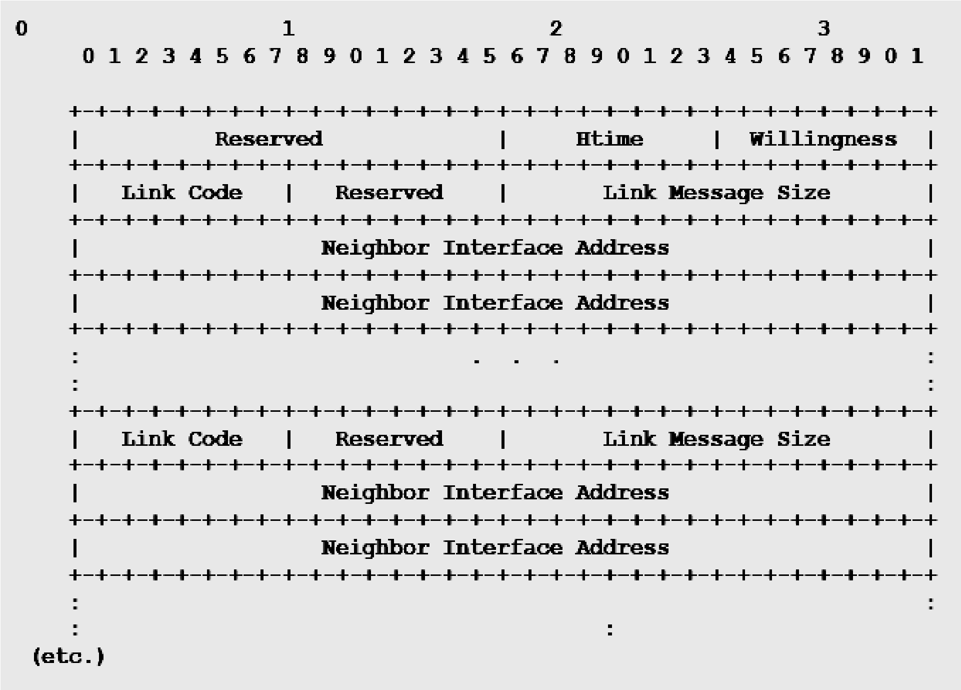
Time To Live: is the maximum number of hops a message will be transmitted.

Hop Count: indicates the number of hops that the message has visited. The originator sets this value to zero.

Message Sequence Number: is the unique identification number, assigned to message by the source.

HELLO messages perform three independent tasks: link sensing (between a node’s interface and neighboring interfaces), neighborhood discovery, and MPR selection signaling. Link sensing and neighbor detection offer each node a list of neighbors with which the node can directly communicate and afterwards the algorithm of selecting MPRs is taking place. Basically, an MPR is selected in a way that ensures that all the messages broadcast by a node that is a selector of this MPR will be received by all nodes within a distance of 2 hops from the source node.

The HELLO message is encapsulated inside an OSLR packet and, in that case, the Message-type field of the packet is set to `HELLO_MESSAGE`. Figure 3 shows the format of a HELLO message.



```
0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1

  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |          Reserved             |     Htime     |  Willingness  |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |   Link Code   |   Reserved    |       Link Message Size       |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                  Neighbor Interface Address                   |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                  Neighbor Interface Address                   |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  :                             .  .  .                           :
  :                                                               :
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |   Link Code   |   Reserved    |       Link Message Size       |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                  Neighbor Interface Address                   |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                  Neighbor Interface Address                   |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  :                                                               :
  :                                       :
 (etc.)
```

Figure 3. OSLR HELLO Message Format [RFC 3626]

Reserved: all 0s.

Htime: is the time between two HELLO messages sent by a node.

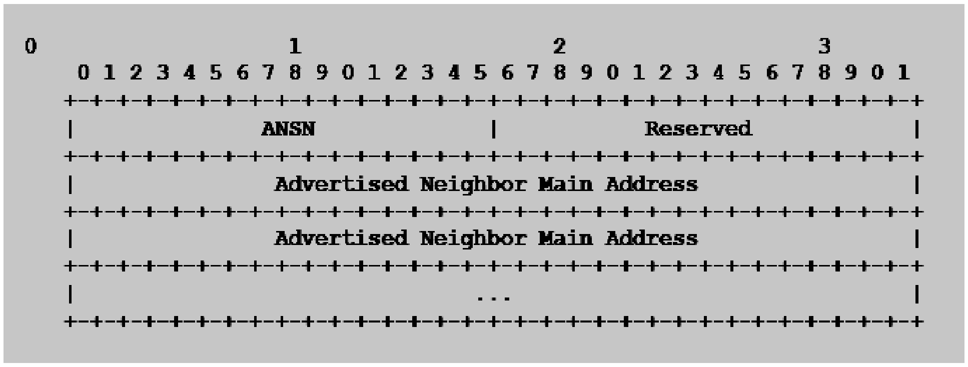
Willingness: specifies the willingness of a node to carry and forward traffic for other nodes. Possible values are `WILL_NEVER, WILL_ALWAYS, MUST,` and `WILL_DEFAULT.`

Link Code: specifies information about the link between the interface of the sender and a subsequent list of neighbor interfaces. It also specifies information about the status of the neighbor.

Link Message Size: is the size of the link message, counted in bytes and measured from the beginning of the "Link Code" field and until the next "Link Code" field.

Neighbor Interface Address: is the address of an interface of a neighbor node.

In OLSR, each node keeps network topology information in a table that is used for routing-table calculations. This topological network information is disseminated in the network with TC-type messages. A node must disseminate network topological information between itself and the nodes in its MPR-selector set. Like all the previous type of messages, TC messages are encapsulated in an OLSR packet, where the field message type is set to `TC_MESSAGE.` Figure 4 shows the TC-message format.



```
0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |              ANSN             |           Reserved            |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |               Advertised Neighbor Main Address                |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |               Advertised Neighbor Main Address                |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                              ...                              |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

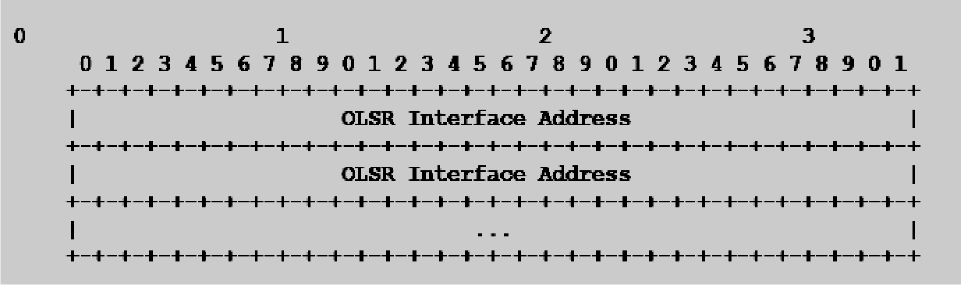
Figure 4. OSLR TC Message Format [RFC 3626]

Advertised Neighbor Sequence Number (ANSN): The sequence number for keeping up-to-date information about a node’s neighbor set.

Advertised Neighbor Main Address: The main address of a neighbor node.

Reserved: Default value is set to 0000000000000000.

We saw above that a node running OLSR might have more than one OLSR interface (network device). When a node has just one OLSR interface, the address of the interface is the “main” address of the node. However, when a node has multiple interfaces, it chooses one of those addresses to be the node’s “main” address. The resolution between multiple interface addresses and the node’s main address is done by exchanging Multiple Interface Declaration (MID) messages. Every node with multiple interfaces periodically announces information describing its interface configuration to other nodes in the network. MPRs are assigned to accomplish this task. Figure 5 shows the format of an MID message.

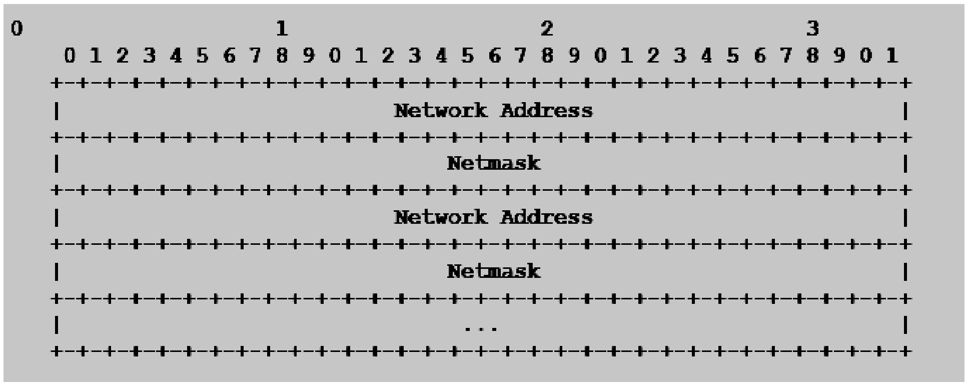


```
0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                    OLSR Interface Address                     |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                    OLSR Interface Address                     |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                              ...                              |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 5. OSLR MID Message Format [RFC 3626]

OLSR Interface Address: Contains the address of an OLSR interface of a node, excluding the node’s main address (which is already indicated in the originator address).

To provide interconnection with other routing domains when a MANET is used to expand existing wired or wireless networks, a node uses a Host and Network Association (HNA) message. The `HNA_MESSAGE` is encapsulated in the same way as other types of messages, in an OLSR packet. Figure 6 shows the Host and Network Association (HNA) message format.



```
 0                   1                   2                   3
   0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                         Network Address                       |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                             Netmask                           |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                         Network Address                       |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                             Netmask                           |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  |                              ...                              |
  +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

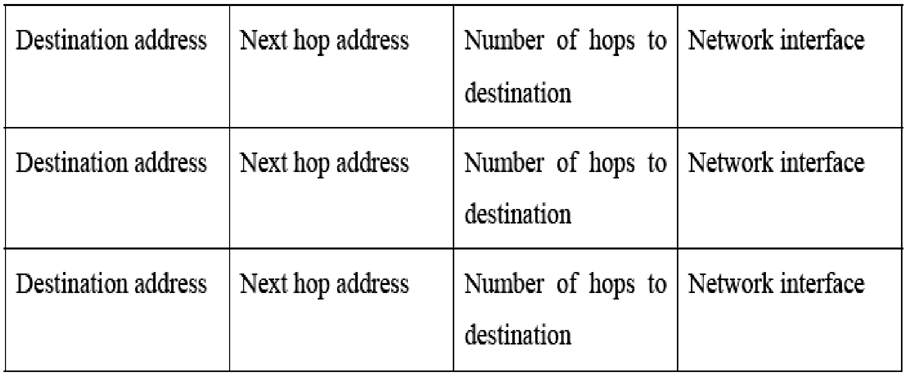
Figure 6. OSLR HNA Message Format [RFC 3626]

Network Address: The network address of the associated network.

Netmask: The net mask, corresponds to the network address immediately above it.

d. Route Discovery and Maintenance

Each node in a network maintains a routing table that enables a source node to send data packets to a destination node. Four different types of information are used for the construction, calculation and maintenance of routing information. Every node in the network obtains all the information necessary for the construction of its routing table with a periodic transmission of messages. The node, upon receiving this information, updates and recalculates its routing table. As we described above, paragraphs MPRs are assigned this task. When a link breaks or if the network topology changes due to a change in a node position in the network, no messages other than those defined above are required for the update of the routing table. Figure 7 shows the structure of a node's routing table in OLSR.



Destination address	Next hop address	Number of hops to destination	Network interface
Destination address	Next hop address	Number of hops to destination	Network interface
Destination address	Next hop address	Number of hops to destination	Network interface

Figure 7. OSLR Routing Table [RFC 3626]

e. Security

OLSR does not provide security mechanism to ensure that nodes do not intentionally provide false routing information. OLSR designers assume that there are already additional security mechanisms in place at the lower layers of the network. However, any persistent attack to any of the MPRs will result in flooding false link state information to other nodes. We will see further in the next sections that most of the proposed routing protocols for MANETs depend for their proper function on additional security mechanisms that will be in place in the network.

f. Conclusions

The main advantages of OLSR are low latency and high data delivery ratio because each node in the network maintains an up-to-date routing table with all the destinations in the network. Thus, no additional connection set-up time is required for a node to send data packets to another node in the network. This proactive nature of OLSR makes it a very attractive solution in networks where low latency and high data delivery ratio are the main concerns. However, the main disadvantage of this protocol comes from its proactive nature and the flooding mechanism, despite the use of the MPRs. OLSR may introduce high routing overhead, consuming a large portion of the available bandwidth. OLSR does not support multicasting routing.

2. Destination Sequenced Distance Vector (DSDV)

a. Protocol Overview

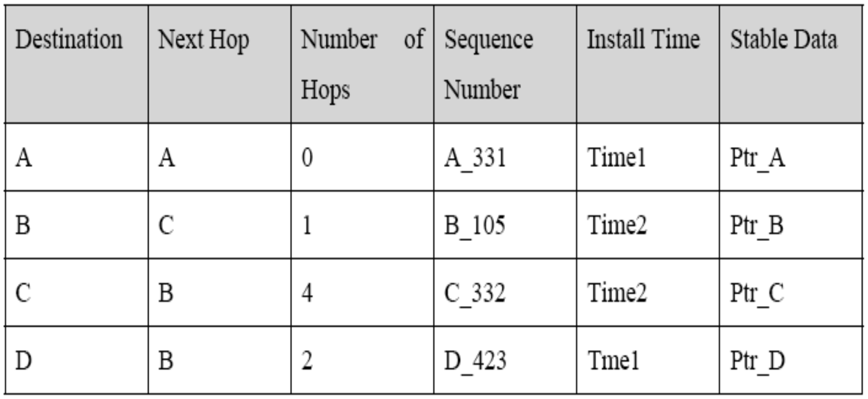
Destination Sequenced Distance Vector [Perkins 1994] is a loop free routing protocol in which the shortest-path calculation is based on the Bellman-Ford algorithm. Data packets are transmitted between the nodes using routing tables stored at each node. Each routing table contains all the possible destinations from a node to any other node in the network and also the number of hops to each destination.

The protocol has three main attributes: to avoid loops, to resolve the “count to infinity” problem, and to reduce high routing overhead. Each node issues a sequence number that is attached to every new routing-table update message and uses two different types of routing-table updates, named “full” and “incremental dumps”, respectively, to minimize the number of control messages disseminated in the network. Each node keeps statistical data concerning the average setting time of a message that the node receives from any neighboring node. The data is used to reduce the number of rebroadcasts of possible routing entries that may arrive at a node from different paths but with the same sequence number. DSDV takes into account only bidirectional links between nodes.

b. Route Discovery and Maintenance

DSDV routing-table construction starts with the condition that every node in the network periodically exchange control messages with its neighbors to set up multi-hop paths to any other node in the network, in accordance with the Bellman-Form algorithm. Each individual route to every destination is tagged with a destination sequence number, which is issued by the destination node. Any route to a destination with a higher destination sequence number replaces the same route with a smaller destination sequence number in the node’s routing table, regardless of the number of hops to this destination. Every node immediately advertises any significant change in its routing table, such as a link failure to its neighboring node(s), but waits for a certain amount of time to advertise other changes.

This time, has called the “settling time”, is calculated by maintaining, for every destination, a running, weighted average of the most recent updates of the routes. By implementing this advertising scheme, DSDV tries to minimize the number of route updates transmitted by a node. Thus, when a node receives a route update for a destination from one of its neighboring nodes, and a few seconds later, it receives a second update from a different neighboring node for the same destination with the same destination sequence number, but a lower number of hops, the node does not immediately broadcast the change in its routing table. This is highly possible in a MANET, in which the network topology changes very dynamically. If this kind of policy were not in place, the node would have to advertise two route updates within a short period, causing its neighboring nodes to broadcast new route updates to its neighboring nodes. For this purpose, each node maintains a table with the destination address, the last settling time and the average settling time of this address. The node uses the information in this table to check the stability of the route to a destination. Figure 8 shows the structure of a node's routing table.



Destination	Next Hop	Number of Hops	Sequence Number	Install Time	Stable Data
A	A	0	A_331	Time1	Ptr_A
B	C	1	B_105	Time2	Ptr_B
C	B	4	C_332	Time2	Ptr_C
D	B	2	D_423	Tme1	Ptr_D

Figure 8. DSDV Routing Table

Destination: The destination node.

Next Hop: The next hop to this destination.

Number of Hops: The number of hops to this destination.

Sequence Number: The sequence number issued by the destination node.

Install Time: When this entry was made.

Stable Data: A pointer to the previous table.

As the position of a node in a network constantly changes over time, each node needs to advertise to its neighboring nodes any change in its routing table. However, this approach can lead to a high overhead of control messages in the network, leaving no available bandwidth for user data. Thus, DSDV designers came up with the concept of full and partial routing-table advertisement. Within this design, each node that encounters a change in the path to any destination may choose to advertise only this particular change instead of its complete routing table. This partial advertisement of a node's routing table is called an "incremental update." If many changes occur in a node's routing table, the node may choose to advertise full routing-table entries, called a "full update," instead of many incremental updates.

c. Security

DSDV does not provide security mechanism to address security vulnerabilities observed in MANETs. [Wang 2003] suggested that DSDV is vulnerable to any malicious node that disseminates false routing updates due to periodic exchange of routing-update massages. Thus, an attack to replace the destination sequence number in a route-update packet may have a severe impact on the performance of the network.

d. Conclusions

DSDV has certain advantages that cannot be overlooked. First, the simplicity of the protocol is very similar to the classic Distance Vector, with only small modifications to avoid loops, with the use of destination sequence numbers. DSDV also presents low latency, as every node always has a route to any destination in the network. However, DSDV does not scale well in networks with high mobility, as the broken links create a "storm" of route updates. This situation may severely degrade network performance, in which the available bandwidth is limited. Another disadvantage of DSDV is that it does not support a sleeping mode, as every node in the network must periodically broadcast changes or full updates of its routing table. Those frequent and periodic route updates in the network will also result in high-energy consumption. Finally, DSDV does not support multicasting routing.

3. Cluster-Head Gateway Switch Routing Protocol (CGSR)

a. Protocol Overview

The routing protocols we have studied so far use a flat network topology in which all nodes are assigned the same tasks in terms of the route discovery and maintenance process. OLSR differs from other proactive protocols by the introduction of multiple point relays. However, every node in a network with flat hierarchy must maintain, in the worst case, a route to every possible destination in the network. As more nodes join the network, the size of the routing-tables increases, resulting in large numbers of control messages in the network.

Clustering can increase the scalability of a MANET because the network can be divided into different groups of nodes. In a clustering scheme, these groups are called `clusters.` Chiang, Wu, Liu, and Gerla [1997] introduced one such clustering protocol. For each cluster, there is a node, `clusterHead` that is assigned to act as the leader in the cluster. The cluster head coordinates the channel access of the other nodes within the cluster by implementing a token-based polling protocol. We will see in the next sections the algorithm for selecting the cluster heads within a cluster. Nodes that are located within the boundaries of two or more clusters are called `gateways.` The communication between two nodes in the network is made through the cluster heads and the gateways. Clustering can provide a mechanism to allocate bandwidth among different clusters, improving channel reuse and hierarchical routing.

b. ClusterHead and Gateway Selection Algorithm

In CGSR, the cluster-head selection is made dynamically by employing a Least Cluster Change (LCC) algorithm. The main design objective of this algorithm is to avoid frequent cluster-head changes that will affect the performance of the protocol. Thus, under this algorithm, in the initialization state a node becomes a cluster head by the use of either a lower-id clustering algorithm or a highest-connectivity clustering algorithm. When a node that is neither a cluster-head nor a gateway gets isolated from all other clusters, it forms its own cluster and becomes a cluster head. When a cluster head moves away from its cluster to a neighboring cluster, it challenges the neighboring cluster head and one of them will give up its property as indicated by the applied clustering algorithm. Under the LCC algorithm when a cluster "member node," a node that is neither a cluster head nor a gateway, alternates its position from one cluster to another, it does not affect the cluster-head status in either of the clusters. Only the membership relationship of the clusters will be affected. Cluster heads have the highest priority among other nodes in a cluster for receiving the token, because they forward all the data packets from the nodes within their clusters.

A `gateway,` as it is located between two or more clusters, should be able to communicate with all the cluster heads in whose clusters it exists as a member. For this reason, a gateway is equipped with multiple radio interfaces to avoid conflicts when the token is passed to the gateway, but it is tuned to another code. Therefore, every node that participates in the network should be equipped with multiple radio interfaces, since every node is expected to shift its status from a single node to either a cluster-head or a gateway, and vice versa. Figure 9 shows the formation of clusters and the three different kinds of nodes in a network.

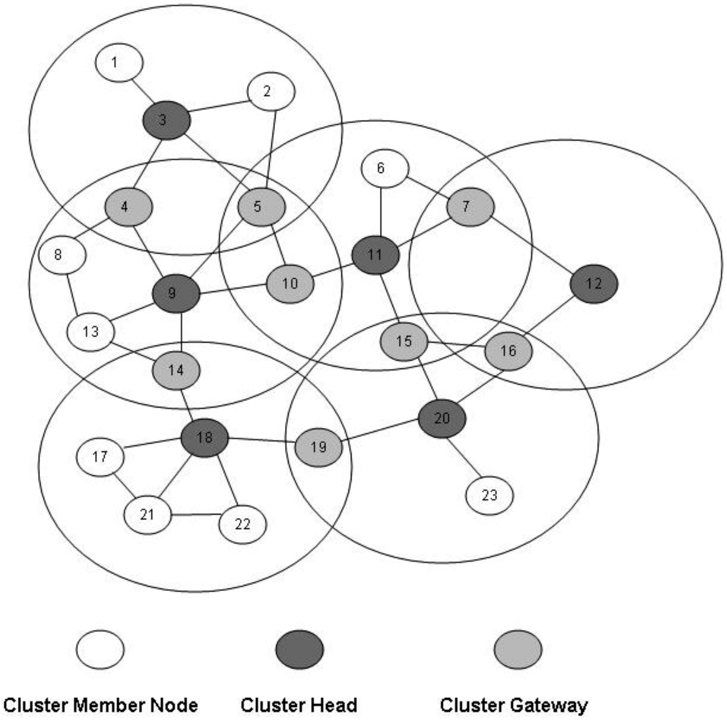


Figure 9. CGSR Clusters Formation

c. Routing

CGSR uses a combination of routing protocols. An extension of DSDV is used for the construction of the routing tables, and the cluster routing protocol is used for the channel accessibility within the cluster. Under DSDV, every node constructs two tables with routing information. The first table contains node membership status, and the second table, next-hop information. The node membership table matches every node in the network with its corresponding cluster head; the second table contains the route, as a list of next-hops, to any destination cluster head in the network. The cluster routing protocol takes its place when a source node has data to send to a destination node. The source node, upon receiving the token from its cluster-head, looks up its routing table and forwards the data packet to its cluster head. Figure 10 shows the route that the data packet follows from source node 1 to destination node 23.

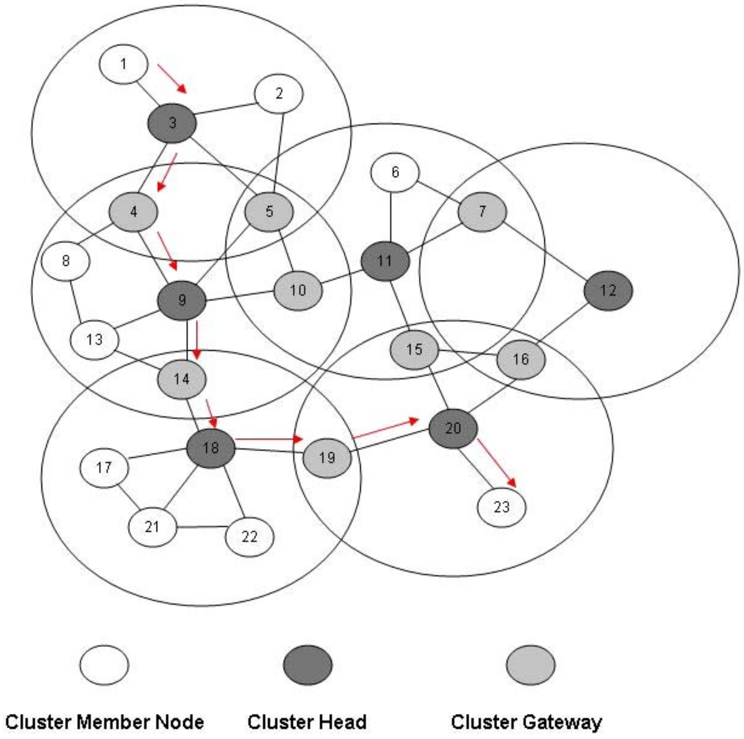


Figure 10. CGSR Routing

We see in Figure 10 that node 1 forwards a data packet to its cluster-head, and then the cluster head forwards the data packet to one of the two gateways, either node 4 or node 5. The decision of which gateway the packet must be forwarded to is based on the cluster head's routing table. Gateway 4 forwards the data packet to the next cluster head in the path, node 9, and so forth. The full path for this data packet is 1-3-4-9-14-18-19-20-23. It follows the pattern $N_1 - C_1 - G_1 - C_2 - G_2 - C_3 - G_3 - C_4 - N_{23}$, in which C_i and G_i are the corresponding cluster-head and gateway, respectively, in the path.

d. Security

CGSR, like other routing protocols we have seen, does not provide any security in the network. An attack can be directed toward a node, a gateway, or a cluster-head. In the first case, the node will not be able to send or receive data, but this will affect only the individual node, not network performance. In the second case, the cluster head will be able to choose an alternate gateway to forward data packets. An attack toward the cluster- head, however, will have severe consequences for network performance, because the absence of the cluster-head in a cluster causes frequent employment of the LCC algorithm.

e. Conclusions

CGSR is a loop-free protocol, as the underlying protocol for populating the routing-table entries is based on the DSDV, a loop free protocol. CGSR has certain advantages over the other proactive protocols. First, it enables hierarchical routing, and the path is recorded at the cluster level instead of at the single-node level, unlike DSDV and OLSR. Second, this hierarchical scene can be used to implement a hierarchical addresses scene. Hierarchical routing offers greater route robustness, resulting in a lower dissemination of control messages for route repairs, and thus, more available bandwidth for user data. Hierarchical addressing may offer more than one address for a single node when the node is a member of two or more clusters. Therefore, at least one of these addresses will be valid at any given time.

On the other hand, if a cluster-head has the same energy capabilities as its cluster members, it will soon be out of order, as it will have to forward packets from every node within its cluster.

CGSR clustering architecture provides a proper scheme for tactical communications. In tactical scenarios, nodes in fact form a cluster e.g. a Platoon. The Commander of the Platoon can play the role of the cluster-head, and his left, right, front, and back limit then represent the gateways. Their communication devices can be preconfigured and equipped with extra power sources and network interfaces to make them able to perform these extra tasks. To avoid a single point of failure, two or three nodes in the Platoon can be equipped with the same devices, to act as back-up for both the cluster head and the gateways. This scene can also be expanded to create backbone links between the Platoons in a Company and between Companies and the Battalion, even when clusters do not necessarily overlap. Figure 11 shows a tactical implementation of CGSR protocol. Nodes 5 and 21, 7 and 21, 15 and 10, are out of range and cannot set up a link.

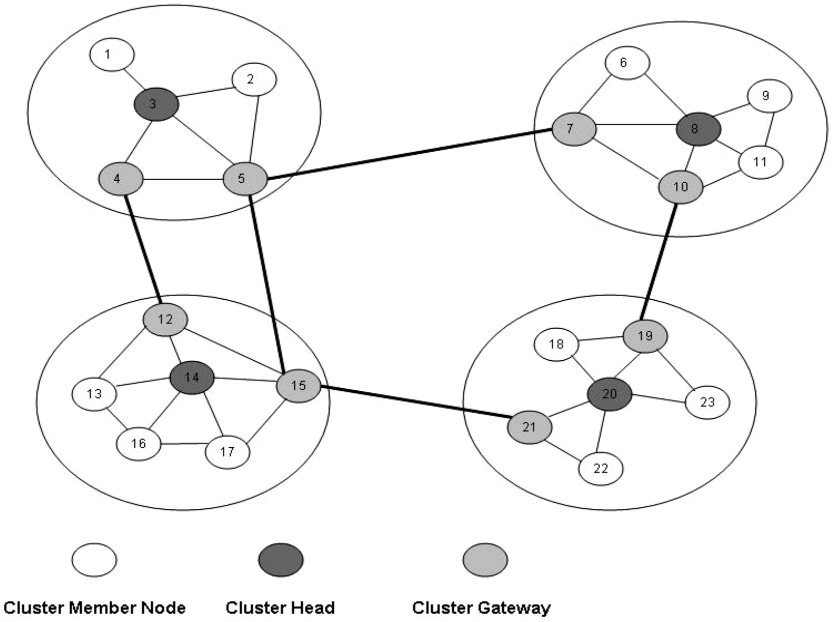


Figure 11. CGSR Tactical Implementation

4. Comparison of Proactive Routing Protocols Based on Qualitative Metrics

All the above proactive protocols are loop-free. OSLR, as a modification of the link state algorithm, does not introduce any loops into the routing process, except for oscillations when the link costs depend on the amount of traffic carried by the link. In the MANET scheme, however, link cost depends on the number of hops from a source to a destination, thus avoiding oscillations. DSDV solves the pathologies that the Distance Vector algorithm introduces, by the use of destination sequence numbers. CGSR uses DSDV as the underlying routing protocol, and thus it accordingly does not suffer from any kind of loops in the network.

The proactive behavior of these protocols is guaranteed by the periodic exchange of control messages. At any given time, every node has at least one route to any possible destination in the network. We say “possible destination” because the physical existence of a node in the network does not necessarily mean that the node is active or that a route to the node exists, because the node may be out of the transmitting range of all other nodes in the network.

None of the above protocols addresses the security vulnerabilities that are obvious in wireless networks. The proper function of these protocols is based on an assumption that all the nodes exist and operate in a secure environment where link-and physical-Layer security mechanisms are in place. However, CGSR seems to be the most vulnerable amongst DSDV and OLSR and, as explained in the previous sections, an attack on nodes that act as cluster heads may have sever consequences for network performance. DSDV is more secure than OLSR, as OLSR functionality is based on the proper behavior of the MPRs.

DSDV and CGSR do not support unidirectional links. However, in wireless communication, unidirectional links will exist and should be supported to take advantage of any possible paths from a source node to a destination node. In MANETs, especially, there is no such “luxury” as ignoring any possible paths, as routing protocols should take advantage of any link to calculate routes in the network. OLSR designers take into account these limitations of the wireless network and support both bidirectional and unidirectional links.

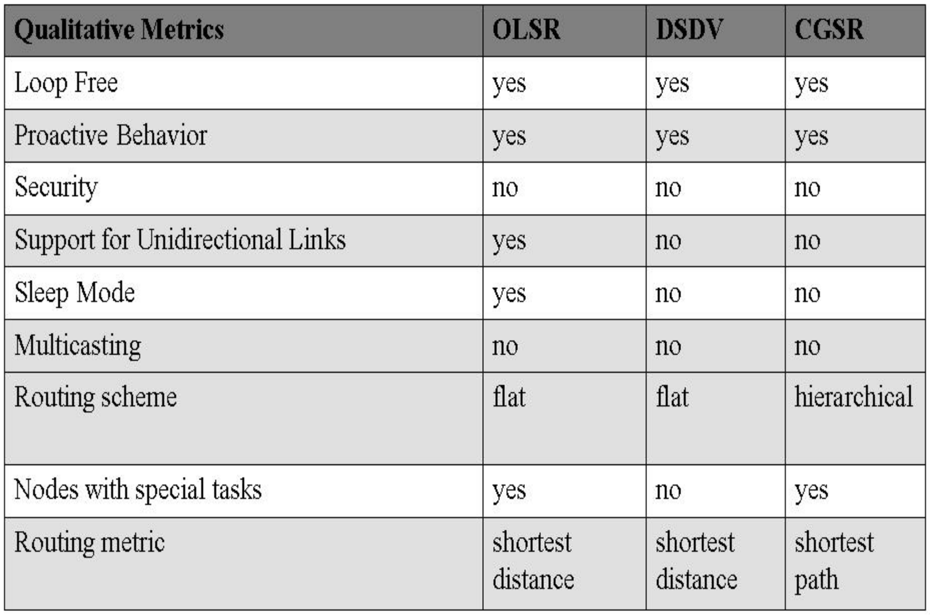
As for the “sleep mode” operation, only OLSR considers some extensions in its current existing design to support such an operation. In a wireless ad-hoc network, in which nodes depend mainly on batteries for their energy source, the sleep mode is a serious attribute that should be supported by any routing protocol.

Multicasting is not considered by any of the above protocols. In real situations in tactical communications, data will be destined to a group of nodes, rather than to an individual node. Unicasting will decrease the bandwidth available for user data when the same message has to be delivered to multiple nodes.

We have also added three additional metrics, to point out the differences in the design and implementation of the three protocols. We saw in the precious chapter why the hierarchical routing philosophy of CGSR is better than the flat routing philosophy of DSDV and OLSR.

The security and robustness of the protocol are also connected to the issue whether or not the protocol functionality depends on nodes with “special” or “crucial” tasks. Both OLSR and CGSR have nodes with special tasks.

The way that all the above protocols calculate their routes from a source node to a destination node follows the shortest distance approach, which computes the smallest number of hops between the source and the destination. However, as CGSR follows a cluster head-to-gateway pattern for forwarding packets, it increases the number of hops between a source and a destination node. Table 1 summarizes the performance of the above protocols, based on qualitative metrics.



Qualitative Metrics	OLSR	DSDV	CGSR
Loop Free	yes	yes	yes
Proactive Behavior	yes	yes	yes
Security	no	no	no
Support for Unidirectional Links	yes	no	no
Sleep Mode	yes	no	no
Multicasting	no	no	no
Routing scheme	flat	flat	hierarchical
Nodes with special tasks	yes	no	yes
Routing metric	shortest distance	shortest distance	shortest path

Table 1. Comparison of Proactive Protocols

By summarizing the above results, we can see that OLSR is closer to the IETF MANET working-group design suggestions. Indeed, OLSR has been designed in high respect to RFC 2501. Perhaps the only visible disadvantage is the high routing overhead.

However, it is mainly up to the network designer to decide what he really needs from a network. In tactical communications, where the main concerns are timely and reliable data delivery, OLSR may fit well as a routing protocol. If the concern is utilization of the biggest portion of the available bandwidth, leaving a small portion for control messages, then OLSR is not the best choice. On the other hand, the CGSR clustering scheme, as shown in Figure 11, is very reflective of an army's structure and communications and could provide a good choice, with of course, a number of extensions and modifications.

Finally, given qualitative metrics and the attributes of the above protocols, we choose OLSR for further evaluation in our simulation.

C. REACTIVE ROUTING PROTOCOLS

1. Ad Hoc On-Demand Distance Vector (AODV)

a. Protocol Overview

Ad Hoc On-Demand Distance Vector, [RFC 3561] , is a reactive routing protocol that is based on the Bellman-Form algorithm and uses originator and destination sequence numbers to avoid both "loops" and the "count to infinity" problems that may occur during the routing calculation process.

AODV, as a reactive routing protocol, does not explicitly maintain a route for any possible destination in the network. However, its routing table maintains routing information for any route that has been recently used within a time interval; so a node is able to send data packets to any destination that exists in its routing table without flooding the network with new Route Request (RREQ) messages. In this way, the designers of AODV tried to minimize the routing overhead in the network caused by the frequent generation of routing control messages.

A third characteristic of AODV is its ability to interconnect nodes in a "pure" MANET running AODV with other non-AODV routing domains, thus extending any network with fixed infrastructure to a network with both mobile wireless nodes and static nodes, e.g., Ethernet.

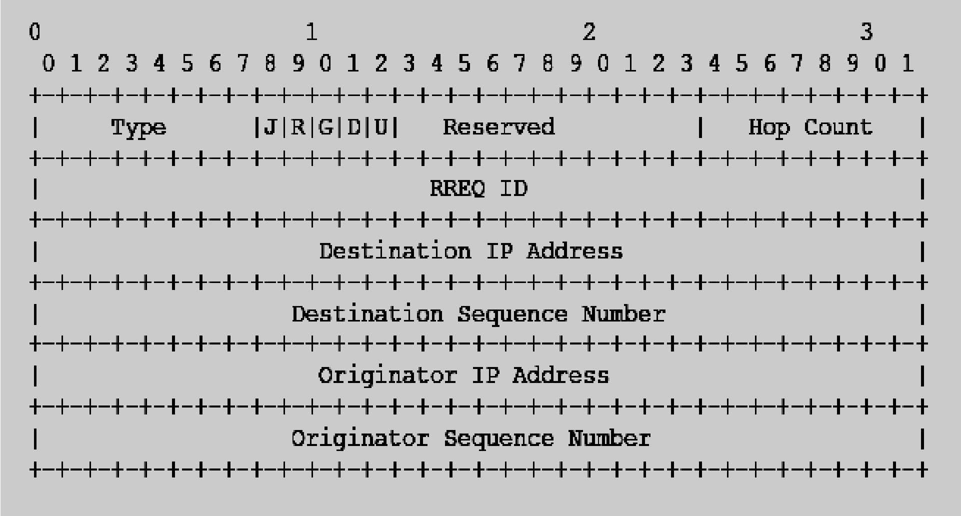
A fourth characteristic of AODV is its support for both unicast and multicast routing.

A final important characteristic of AODV is its ability to support both bidirectional and unidirectional links, as in many cases in wireless communications, two nodes in the network may only communicate with unidirectional links.

b. Messages Format

AODV, unlike OLSR does not introduce any new packet formats, other than control messages encapsulated in an IP datagram. AODV can operate with both IPv4 and IPv6 without any further modification.

Three types of messages are used for route-discovery and link-failure notification: Route Request (RREQ) message, Route Reply (RREP) message, and Route Error (RERR) message. When a sender node does not have a valid route to a destination node in its routing table, it broadcasts a RREQ message. The destination node, or any intermediate node with a valid route to the destination, replies to the RREQ message with a RREP message. The RERR message is sent by a node to notify other affected nodes when a link failure is detected. Figures 12, 13, and 14 show the formats of the above three messages.



```
0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |J|R|G|D|U|   Reserved          |   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            RREQ ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination IP Address                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP Address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Originator Sequence Number                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 12. AODV Route Request Message Format [RFC 3561]

Type: 1

J, R, G, D, U: Flags

Reserved: All 0s

Hop Count: The number of hops from the originator of the request to the node handling the request

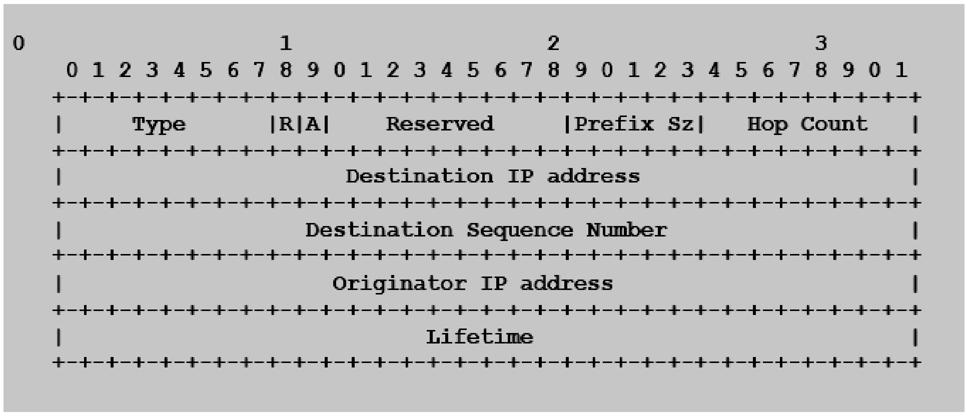
RREQ ID: A unique identifier for the request

Destination IP Address: The address of the node to which the request has been sent to acquire the route to the node

Destination Sequence Number: The last sequence number that is in the originator’s routing table and was issued by the destination node

Originator IP Address: The IP address of the originator

Originator Sequence Number: The current sequence number issued by the originator



```
0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |     Type      |R|A|    Reserved     |Prefix Sz|   Hop Count   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     Destination IP address                    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                  Destination Sequence Number                  |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                    Originator IP address                      |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                           Lifetime                            |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 13. AODV Route Reply Message Format [RFC 3561]

Type: 2

R, A: Flags

Reserved: All 0s

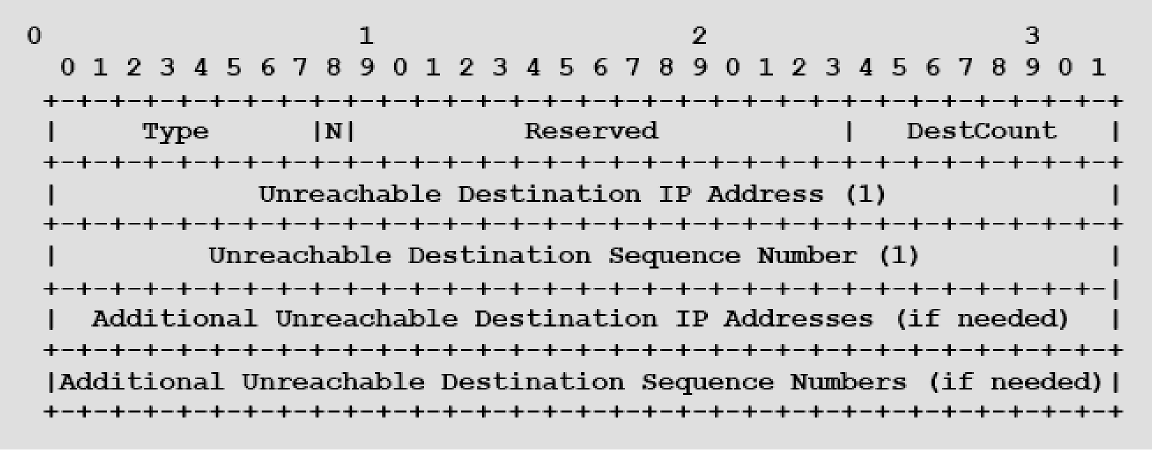
Prefix size: If nonzero, the 5-bit Prefix Size specifies that the indicated next hop may be used for any node with the same routing prefix (as defined by the Prefix Size) as the requested destination

Hop Count: The number of hops from the originator of the request to the destination node

Destination IP Address: The address of the destination node

Destination Sequence Number: The destination sequence number related to the route

Lifetime: The time in mills that the route is considered to be valid



```
0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |N|          Reserved           |   DestCount   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|            Unreachable Destination IP Address (1)             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Unreachable Destination Sequence Number (1)           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-|
|  Additional Unreachable Destination IP Addresses (if needed)  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Additional Unreachable Destination Sequence Numbers (if needed)|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 14. AODV Route Error Message Format [RFC 3561]

Type: 3

N: flag

Reserved: All Os

DestCount: The number of unreachable destinations due to this link failure

Unreachable Destination IP Address: The IP address of the destination that is affected by the link failure

Unreachable destination Sequence Number: The sequence number of the destination in the originator’s routing table

c. Route Discovery and Maintenance

When a node, called here “the originator,” has data to send to another node in the network, called here “the destination,” the originator looks in its routing table to find a route to the destination. If there is no such route, or the route is marked as invalid by an appropriate flag, the originator propagates a RREQ message to its neighboring nodes. The originator, before sending the RREQ message, increments by one the RREQ ID and the originator sequence number in the message header. In this way, each RREQ message is uniquely identified by combining the above numbers with the originator IP address. Any intermediate node that receives an RREQ message, takes one of the following three actions: First, the intermediate node discards the RREQ message if it has previously received the same RREQ message. If the intermediate node has a valid route to the destination node, it reverses a RREP message back to the originator. If the intermediate node does not have a valid route to the destination, it further broadcasts the message to its neighboring nodes. The destination node, which finally receives the RREQ message, increments the destination sequence number and reverses an RREP message back to the originator. When the originator node receives the RREP message, it updates its routing table with the "fresh" route. Figure 15 shows the route discovery process from source node 1 to destination node 10.

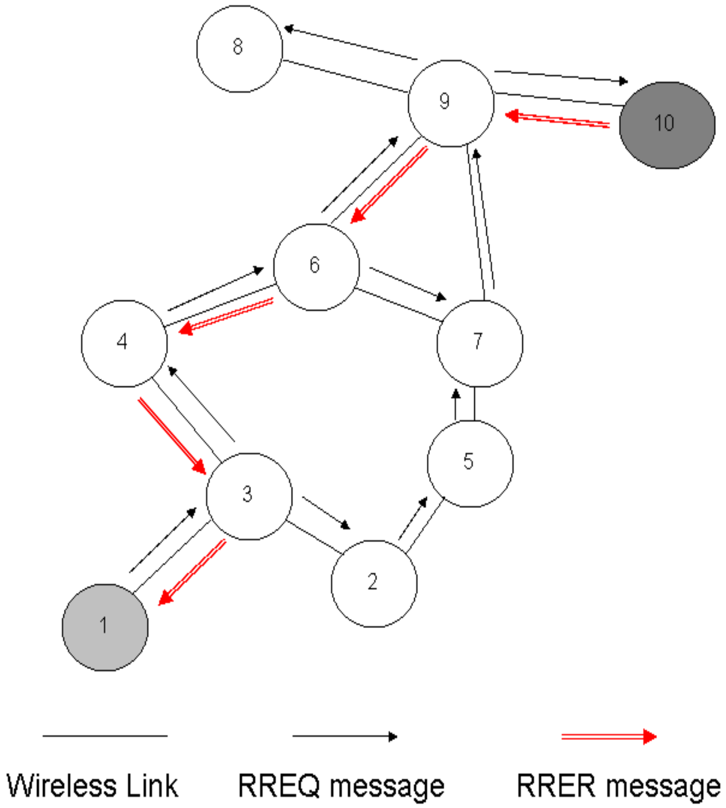


Figure 15. AODV Route Discovery Process

AODV uses mainly two mechanisms to avoid high routing overhead caused by its flooding nature. The first mechanism involves a binary exponential back off to minimize congestion in the network. The second one involves an expanding ring-search technique in which the originator node starts broadcasting a RREQ message and the TTL value is set to a minimum default value. If the originator node does not receive a RREP message within a certain time interval, it exponentially increments the time interval and increases the diameter of the searching ring. The maximum value for the ring diameter is set by default to 35, which is, for AODV, the maximum value of the network diameter. The route maintenance process in AODV is very simple. When the link in the path between node 1 and node 10 breaks (Figure 16) the upstream node that is affected by the break, in this case node 4 generates and broadcasts a RERR message. The RERR message eventually ends up in source node 1.

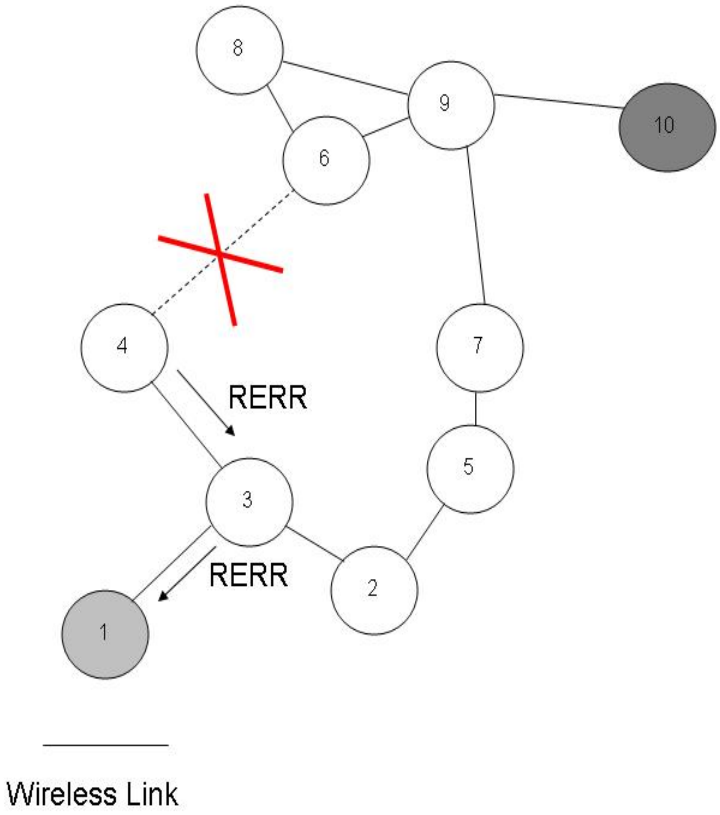


Figure 16. AODV REER Message Generation

Upon receiving the REER message, node 1 will generate a new RREQ message.

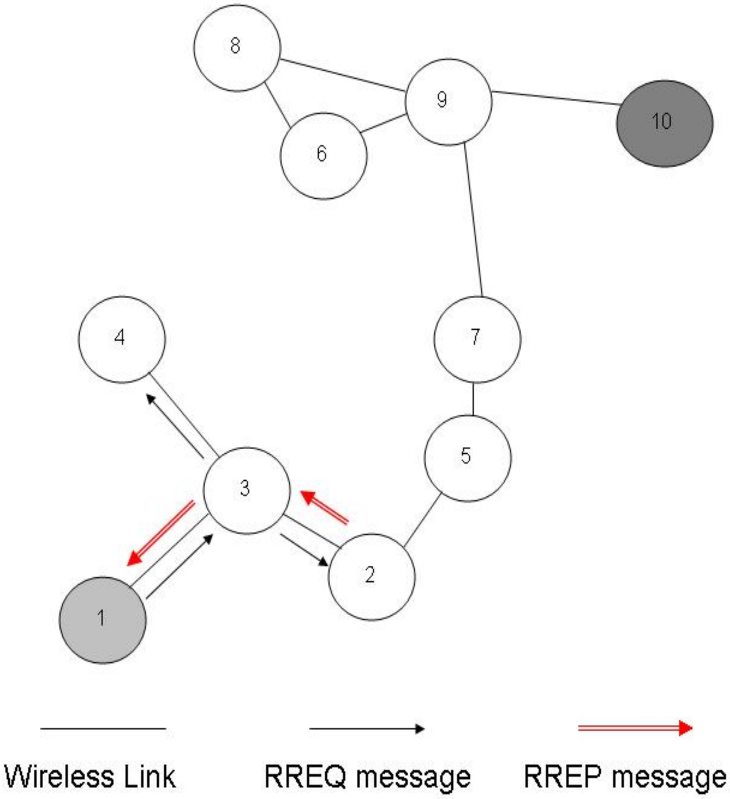


Figure 17. AODV Route Maintenance Process

Finally, if node 2 already has a route to node 10, it will generate a RREP message, as indicated in Figure 17. Otherwise, it will re-broadcast the RREQ, as in Figure 15.

d. Security

AODV does not address any security vulnerabilities that exist in the ad-hoc wireless networks. AODV designers assume that all nodes in the network are trusted, and that security policies and mechanisms are already in place. M. G. Zapata [2004] proposed security enhancements for AODV. The basic idea is to use a public key infrastructure to verify the integrity and authenticity of the AODV control messages. With this protocol's extensions, each node has to verify any control message that it has received from its neighboring nodes before further broadcasting the message. Although the scope behind S-AODV is obvious, there are certain issues that we point out. First, the use of public key infrastructure in such wireless networks is not as simple as it looks at first sight. Second, the whole procedure will create further delay in the network, due to greater processing time at the intermediate nodes. For tactical communications, the use of symmetric keys at the lower Layers seems to be a more preferable solution.

e. Conclusions

The two main advantages of AODV are its reactive nature, which reduces the routing overhead in the network and the use of destination sequence numbers that address routing loops and the "count to infinity" problem. However, control message overhead can be introduced when every intermediate node originates a RREP message, to satisfy a route discovery request if it has a valid route to the destination, causing a RREP messages "storm". Another disadvantage of AODV is that the propagation of periodic HELLO messages from a node, to maintain connectivity with its neighboring nodes, will lead to bandwidth consumption.

In conclusion, the simple design, the low routing overhead and the ring searching technique make AODV an attractive solution for networks in which the available bandwidth is limited and nodes can form organized groups. Security weaknesses can be addressed by either modifying the protocol with the proposed security extensions, or by applying security mechanisms at the lower layers.

2. Dynamic Source Routing Protocol (DSR)

a. Protocol Overview

Dynamic Source Routing [Johnson, Maltz, and Broch 2004] is a simple reactive protocol that is based on two main mechanisms: route discovery and route maintenance. Both mechanisms are implemented in an ad-hoc fashion and in the absence of any kind of periodic control messages. The main concept of the protocol is "`source routing`", in which nodes place in the header of a packet the route that the packet must follow from a source to a destination. Each node `"caches"` the routes to any destination it has recently used, or discovered by overhearing its neighbors' transmission. When there is not such route, a route discovery process is initiated. The protocol is designed for a MANET of up to two hundreds nodes with high mobility rates and is loop-free. Other important attributes of this protocol are its support for unidirectional links and multicasting.

DSR can provide interconnection of wireless devices with multiple network interfaces. This is an important attribute for tactical communications, as nodes in the military need to have different signal ranges and thus different network devices.

b. Route Discovery

When a node, "the originator," wants to send a data packet to another node in the network, "the destination," it first looks in its `Route Cache` to find a route to the destination. If such a route exists, the originator attaches to the packet header the complete route to the destination and forwards the packet to the next node. The next node checks the packet header and forwards the packet to the next node. The process terminates when the packet reaches the destination.

If the originator cannot find a route to the destination in its Route Cache, it initiates a route discovery process: it broadcasts a route request (RREQ) to its neighboring nodes, adding a unique request ID to prevent other nodes from transmitting the same request. Each of the neighboring nodes checks in its Route Cache, and if it finds such a route, it sends a Route Reply (RREP) message back to the originator with the complete path to the destination. Otherwise, the destination node is obliged to do this task. DSR, by default, determines that a node may retransmit a RREQ message up to sixteen times. However, to avoid a big number of control messages being disseminated in the network, and sometimes for an inactive node, DSR uses expanding ring and exponential back off mechanisms in the route discovery process. We have seen that AODV also uses these two mechanisms for the same purpose.

In Figure 18, we assume that there is no path from source node 1 to destination node 10, so node 1 initiates the routing discovery process. Node 9 discards the RREQ message forwarded by node 7, as it has already received the same message from node 6.

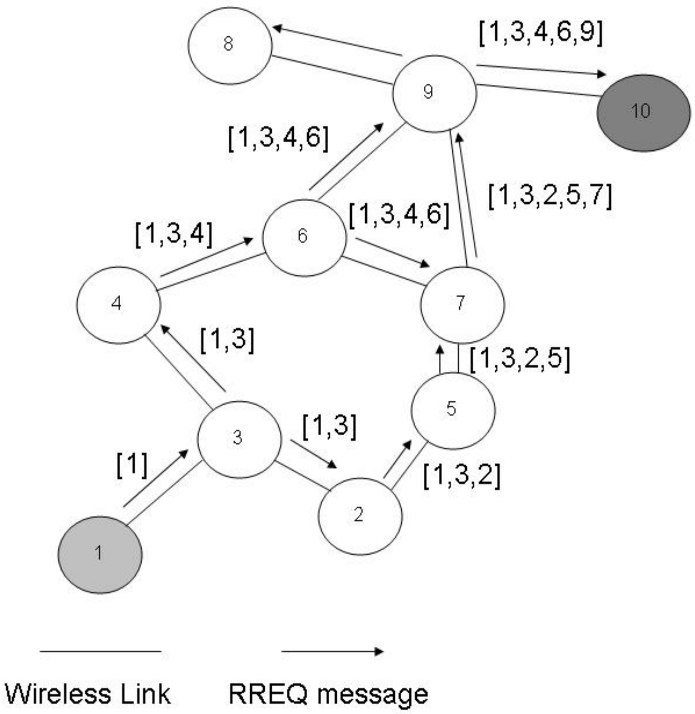


Figure 18. DSR RREQ Message Broadcasting

When node 10 receives the RREQ message, it initiates a RREP message and attaches in the packet header the reverse path to node 1. Figure 19 shows the RREP message process.

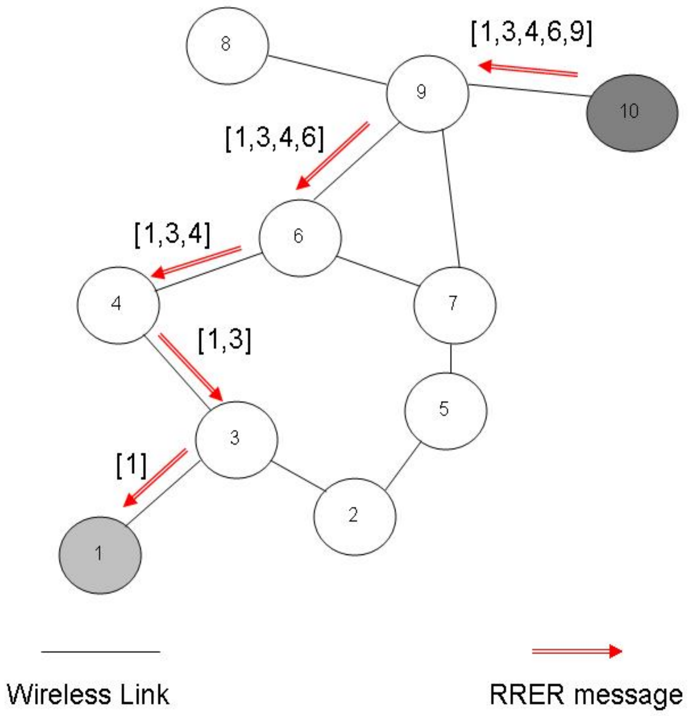


Figure 19. DSR RREP Message Processing

The wireless network device can contribute to the routing discovery process by setting itself in a promiscuous mode, in which a node overhears transmission from neighboring nodes. DSR takes advantage of this mode by caching for future use any new route or multiple routes to the same destination. Thus, when a link breaks during transmission, the originator may be able to find an alternate route to the destination before sending a RREQ message. However, this design may lead to even greater latency if, for instance, the originator tries multiple invalid paths before finally sending a new RREQ message.

c. Route Maintenance

Route maintenance in DSR is based on a distributed manner, by which each node that originates or forwards a packet to the next node is responsible for monitoring the validity of the link between the two nodes. This task can be achieved with or without the exchange of acknowledgment messages between the two nodes. DSR may use such an acknowledgment mechanism when it is already in place, as a standard of the Layer 2 protocol (IEEE 802.11), or by overhearing the next node's retransmission of the packet, “passive acknowledgment,” provided there is a bidirectional link between the transmitting and receiving node. If such mechanisms are not present, the transmitting node can explicitly request an acknowledgment from the receiving node.

When the link between the two nodes breaks and the transmitting node does not receive an acknowledgment from the receiving node, it retransmits the packet a number of times, up to a threshold limit. When, after a certain number of retransmissions, the node does not receive an acknowledgment, it first removes the route from its cache and then originates a Route Error (RERR) message to inform all other nodes that use this link to remove the route from their caches.

DSR has additional route maintenance features to improve its functionality. A “packet salvaging” mechanism includes the actions taken by any intermediate node when a link-break event is detected. Then the intermediate node, after sending the Route Error (RERR) message, may search in its own route cache to find a new route to the destination. When such a route exists, the intermediate node replaces the original source route on the packet with the new route, marks the packet as “salvaged” to prevent unnecessary retransmissions of the same packet by other nodes, and forwards the packet to the new next node. An “automatic route shortening” mechanism starts when any node in a route from a source to a destination detects that there is a shorter path than the one indicated in the packet header from that node to the destination. In that case, the node replaces the original source route with the new one and sends a Route Reply (RREP) message back to the originator to update its route cache. The source node uses “increased spreading of Route Error (RERR) messages” when it receives a Route Error (REER) message. In that event, the originator piggybacks the RERR message on the new RREQ, to prevent other nodes from generating RREP messages with the stale route that caused the REER message.

d. Security

Like many other routing protocols, DSR does not include a built-in security mechanism to address MANET security vulnerabilities. The DSR designers assume that all nodes that participate in the network are trusted and, if not, Layer 2 or physical security mechanisms shall to be in place.

S. Buchegger and Le Boudec [2002] suggest security enhancements for DSR, named CONFIDANT (Cooperation of Nodes, Fairness in Dynamic Ad-hoc Networks), by which nodes monitor the behavior of their neighboring nodes and keep statistical data to measure their neighbor's contribution to the routing process. Based on those metrics, nodes that detect the misbehavior of neighbors propagate an ALARM message to inform other nodes in the network. Though conceptually correct, any such built-in security functionality will increase the processing time and control messages overhead in the network and although CPUs are getting more powerful today the additional control messages with absorb a portion of the available bandwidth for user traffic.

e. Conclusions

The main advantage of DSR is the absence of any periodic control messages that would take over a portion of the available bandwidth. The route discovery and maintenance optimization techniques further eliminate the propagation and dissemination of control messages. However, DSR does not employ any local repair of a broken link and as any intermediate node can respond with a RREP message to a RERR message, based on its route cache, there is a possibility for unstable routes in the network.

DSR was designed for a network with a limited number of nodes. High mobility in the network will cause frequent link breaks that will result in high routing overhead.

For tactical communications with low to medium mobility, DSR can be one of the candidate protocols, as it does not require high-energy consumption because of the lack of periodic updates. It can support multiple network interfaces, which are very common in such communications, and it has low routing overhead, leaving useful bandwidth for user traffic. The security vulnerabilities are the same as with all other proposed routing protocols, and the solution is again symmetric or asymmetric key infrastructure, or the security enhancements proposed in S. Buchegger and Le Boudec [2002].

3. Temporally Ordered Routing Protocol

a. Protocol Overview

All the routing protocols we have studied in the previous chapters are based on link-state or distance-vector algorithms that find the shortest path, which is the smallest number of hops between a source and a destination node in the network. Temporally Ordered Routing Protocol, V.D. Park and M.S. Corson [2001], is a distributed routing protocol that is based on the link reversal algorithm. The main concept of this protocol is that the network for any source node can be "visualized" as a Directed Acyclic Graph (DAG) rooted at the destination node. When a link between the source and the destination fails, the nodes reverse the direction of the links and update the previous nodes in the path. Additionally, each node maintains multiple paths to a given destination and is capable of detecting any partitions in the network.

To accomplish such behavior, a value, "height," is associated with each node at all times. These values can be ordered in comparison to the "height" of each neighboring node. Data flow occurs from a node with a higher value to a node with a lower value. When a node cannot detect the height value of one of its neighbors, it does not forward data packets to that node.

TORA disseminates control messages in a small local area, not in the entire network, thus preserving bandwidth and minimizing processing time in the nodes. When a link failure occurs, there is no need for a large-scaled dissemination of control packets, as they can be limited to the small region where the link failure occurs.

TORA requires bidirectional links between the nodes in the network and synchronization from an internal or external mechanism, e.g., Global Positioning System (GPS). The protocol is loop-free, as the route formation is based on the DAG that is a loop-free data structure, and supports only unicasting routing. TORA has four basic functions: route discovery, route maintenance, route erasing, and route optimization.

Finally, TORA is not a self-operating protocol, but requires the existence of the Internet MANET Encapsulation Protocol (IMEP) as the underlying network layer protocol. [S. Corson, S. Papademetriou, P. Papadopoulos, V. Park, and A. Qayyum 1999].

b. Route Discovery

As a reactive routing protocol, TORA does not maintain in advance any route(s) to any destination in the network. When data packets have to be sent from a source to a destination node and there is no such route, the source node broadcasts a query (QRY) packet to its neighboring nodes. This QRY packet is further forwarded from the intermediate nodes and finally reaches the destination node. When the destination node receives the QRY packet, it replies with an update (UPD) packet and sets its distance, “height,” to the destination to the lowest value, as it is the destination node. Any intermediate node that receives the UPD packet sets its distance to the destination to a value higher than the sender’s value of the UPD packet. If any intermediate node has a route to the destination, it replies with an UPD packet and sets accordingly its distance to the destination. Eventually, all nodes in the path will have adjusted their heights, based on the heights of their neighboring nodes, and a DAG from the source to the destination node will be created. Figure 20 is a visual presentation of the DAG formation from source node 1 to destination node 9.

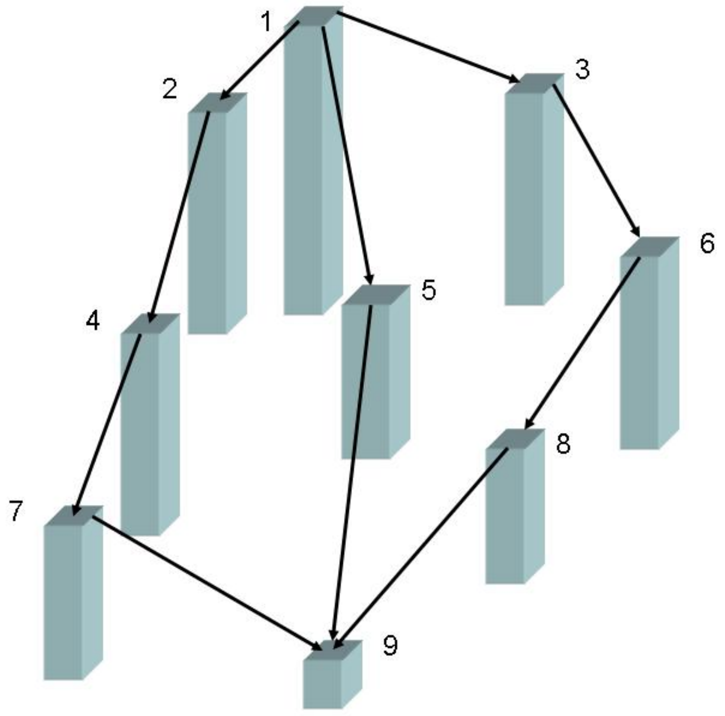


Figure 20. DAG Formation in TORA

Height values [V.D. Park, J.P Macker, and M.S. Corson 1998] are assigned to each node in the paths, and data “flows” from source node 1, which has the higher value, to destination node 9, with zero height value.

TORA also employs a route optimization mechanism by which the destination node initiates the route discovery process by sending an optimization (OPT) packet. The destination node sets its height in the OPT packet and broadcasts the packet to its neighbors. Any intermediate node that receives the packet reselects its height and further broadcasts an OPT packet to the network. The scope behind the optimization function is to enable a proactive behavior in networks with a low rate of topology changes, so that nodes can have in advance one or more routes to any reachable destination in the network.

c. Route Maintenance

Route maintenance in TORA is required when a link failure occurs in the path between the source and the destination node. However, the protocol bounds the link-repair procedure to a small area close to the link failure. If the link between nodes 7 and 9 breaks due to network topology changes, node 7 will reverse the link between itself and node 4, it will change its distance to node 9 to a higher value than its neighbors’ value, and it will generate an UPD message. Node 4, which will receive the message, it will reverse the link between itself and node 2 and will forward an UPD message to node 2, which eventually will reach source node 1. Figure 21 shows the changes in the DAG due to the link failure.

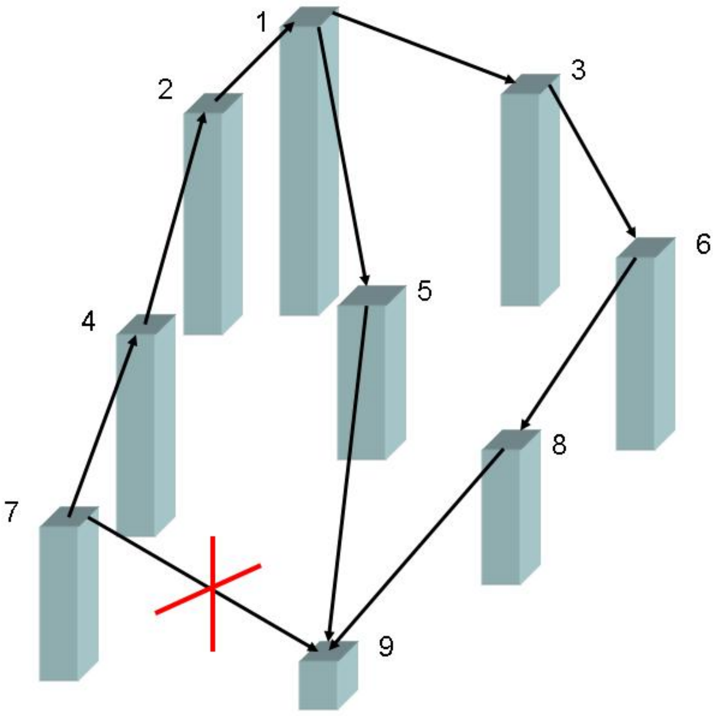


Figure 21. Link Break in TORA

In this example, node 1 has multiple alternate routes to destination node 9 that it will use to continue sending data packets. If node 1 did not have any alternate routes, it would generate a QRY message, as was described in the previous section.

TORA also has the ability to detect any partition in the network. A partition may occur when one or more nodes are unreachable from the source node. In Figure 22, we can see how the protocol reacts when the link between nodes 4 and 2 fails. Node 4 reverses the link between itself and node 2, and sends an UPD message to node 7. However, the link reversal conflicts with the previous one in which the link between nodes 7 and 9 failed. This is an indication of a network partition. When a node detects a partition, it updates its link status table and broadcasts a clear (CLR) message to inform other nodes of the network partition.

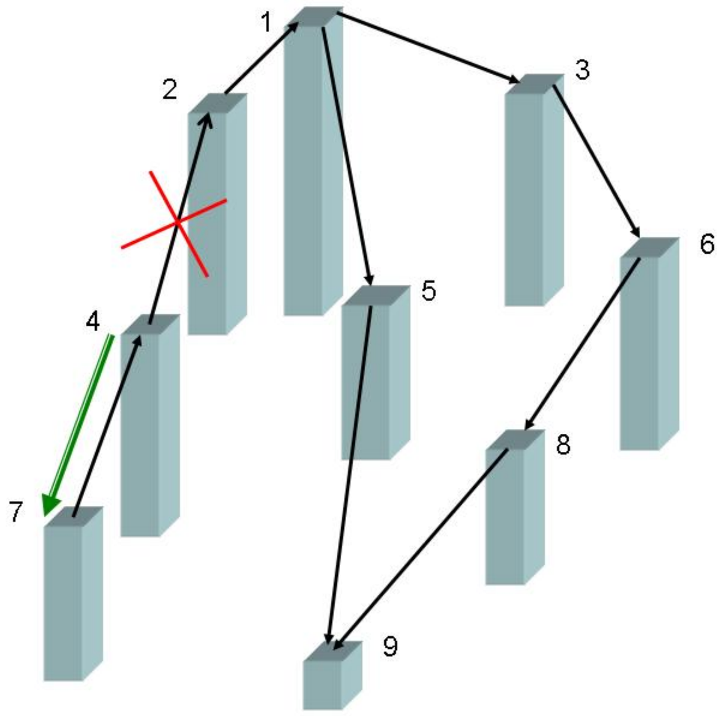


Figure 22. TORA Network Partition Detection

d. Security

The protocol's design does not take into account any MANET security vulnerabilities. This is not surprising, as most ad-hoc routing protocols do not address security problems and leave this issue to be solved by other security mechanisms that can be applied in the network. However, protocol performance issues may arise if the network experiences frequent and concurrent link failures. In that case, the broad dissemination of UPD, and CLR messages in case of network partitions, will create temporal oscillations.

[A. A. Pirzada, C. McDonald 2004] proposed a security encashment for TORA, according to which, every node in the network can be set in promiscuous mode to overhear transmissions of its neighboring nodes. Nodes under this mode can receive additional information concerning the behavior of their neighbors and their contributions to the routing and data packets dissemination process. Thus, nodes can detect any malicious or malfunctioning nodes, based on a comparison between the original and the retransmitted packets. A trusted table is used to stamp each node with a certain trust level.

e. Conclusions

The reactive nature of the protocol, along with its capacity to limit the dissemination of control messages to the region close to a link failure, minimizes the amount of routing control messages in the network. Multicasting and unidirectional-link support are important attributes that TORA does not support. This is regarded as a disadvantage of the protocol. However, TORA could be a good choice for large mobile ad-hoc networks, in which link-state and distance-vector based algorithms will produce a significantly large number of control messages due to frequent changes of the network topology.

4. Comparison of Reactive Routing Protocols Based on Qualitative Metrics

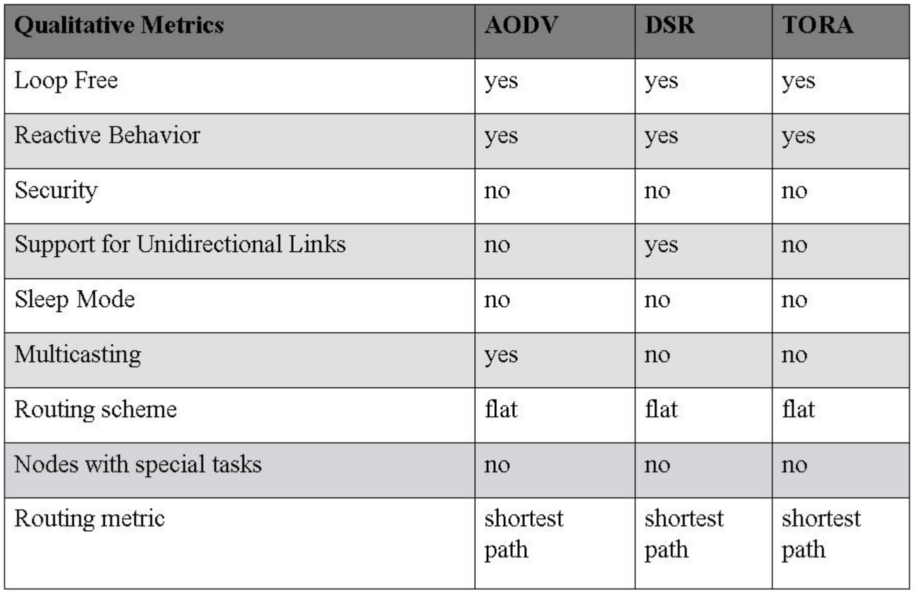
All the above reactive protocols are loop-free. None addresses security vulnerabilities that exist in a wireless ad-hoc network. However, there are certain proposals for providing secure routing at Layer 3 for all the above protocols. Although security is a major concern in military communications, we find that the proposed security mechanisms will increase processing time, power consumption, and latency. Note that reactive routing protocols already suffer from high latency in the network.

Only DSR in its current state, without any modification, can support both bidirectional and unidirectional links. However, DSR will introduce high routing overhead as routing information is stored at the data packets' header. Thus, DSR will not scale well in large networks if communicating nodes are located at opposite edges of the network.

None of the three protocols supports the "sleep mode," another important factor for power preservation, especially in battery-powered mobile nodes. TORA seems to be a more power-effective protocol, as it localizes most of its function in a small area, not in the entire network. However, the exchange of HELO messages by the underlying IMEP protocol will introduce power consumption. AODV will consume more power than DSR due to the exchange of periodic HELO messages.

Only AODV supports multicasting, another important attribute of a routing protocol. None of these protocols depends on any kind of node with special or crucial tasks. All nodes in the network have the same tasks and play the same role in the routing process. This is important, because the lack of “critical” nodes guarantees the inexistence of any single point of failure in the network.

TORA does not necessarily find the shortest path between a source/destination pair, as data flows form nodes with higher height to nodes with lower height. Table 2 summarizes the performance of the above protocols based on qualitative metrics.



Qualitative Metrics	**AODV**	**DSR**	**TORA**
Loop Free	yes	yes	yes
Reactive Behavior	yes	yes	yes
Security	no	no	no
Support for Unidirectional Links	no	yes	no
Sleep Mode	no	no	no
Multicasting	yes	no	no
Routing scheme	flat	flat	flat
Nodes with special tasks	no	no	no
Routing metric	shortest path	shortest path	shortest path

Table 2. Comparison of Reactive Protocols

Finally, given qualitative metrics and the attributes of the three protocols, we suggest that AODV and DSR would be good candidates for the routing protocol in tactical mobile ad-hoc wireless networks. Therefore, we choose both AODV and DSR for further evaluation in our simulation.

D. HYBRID ROUTING PROTOCOLS

1. Zone Routing Protocol (ZRP)

a. Protocol Overview

Zone Routing Protocol [Haas, Z.J., Pearlman, M.R. and Samar, P. 2003] is a distributed routing protocol that combines both a proactive and a reactive scheme for route discovery and maintenance. The basic idea of the protocol is the creation of areas, or zones, where every node proactively maintains one route or multiple routes to any destination inside the zone and reactively obtains routing information for any node outside of the zone. The zone diameter may be defined in advance, before nodes form the network, or it may be optimized by every node, based on ZRP traffic measurements. The radius of a node's zone plays a significant role in the proper behavior of the protocol. If the network consists of a large number of nodes with medium to low mobility or the demand for routes is high, a large value for the radius is preferable to avoid the frequent dissemination of routing requests and reply messages. On the other hand, if the network consists of a small number of nodes with high mobility or the demand for routes is small, the radius value should also be small to avoid overhead of periodic routing update messages.

ZRP consists of two main protocols. The `Intrazone Routing Protocol` (IARP) [Haas, Z.J., Pearlman, M.R. and Samar, P. 2003] is responsible for finding and maintaining valid routes in the internal zones between any source/destination pair at all times. Any proactive routing protocol that we studied in the previous sections, such as DSDV, can be used as the ZRP IARP. The `Interzone Routing Protocol` (IERP), [Haas, Z.J., Pearlman, M.R. and Samar, P. 2003] is responsible for finding any available route outside of the node's internal zone. The scope behind this implementation is to reduce routing overhead and delay and to respond better in the topological changes of the network.

Figure 23 shows the routing zones of node 10 with two different values for the radius. In the first case, where $radius = 2$, node 10 maintains a small number of available routes in its routing table. In the second case, where $radius = 3$, node 10 maintains more routes available in its routing table, in exchange for a larger number of routing update messages. When $radius = 1$, ZRP behaves like a pure proactive protocol.

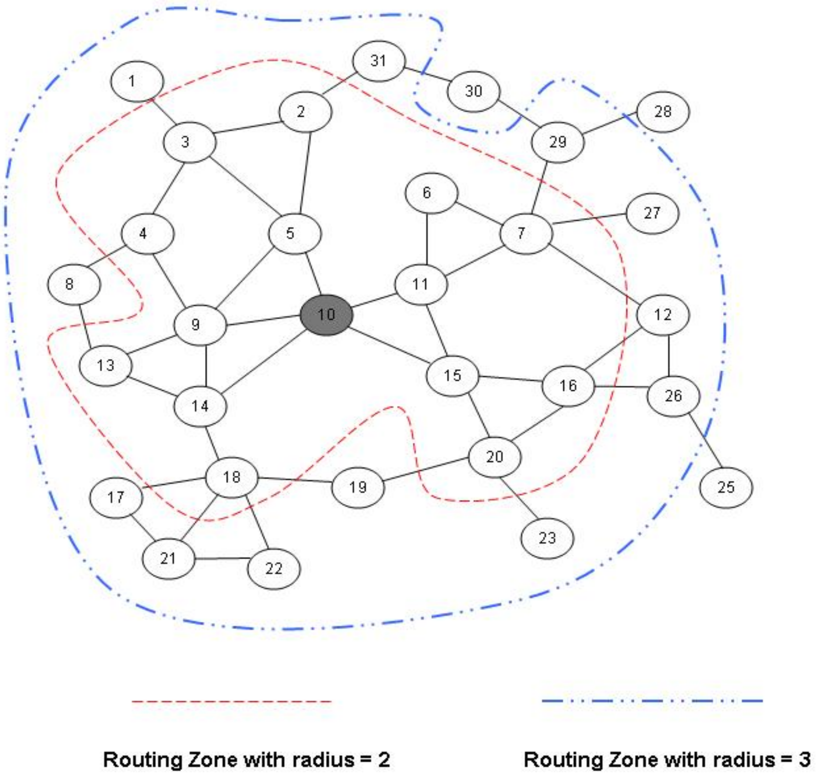


Figure 23. Routing Zones in ZRP

ZRP is a loop-free protocol and provides support for unidirectional links, hierarchical routing, and interconnection with other non-ZRP routing domains when every node's network interface is assigned a unique IP address.

b. Route Discovery and Maintenance

The route discovery process in ZRP depends on the location of the destination node. If the destination node is located inside the source node's intra zone, the protocol acts like any other proactive protocol, thus ensuring that there is always a route to any destination in the intra zone. When the destination node is located outside of the source's intra zone, the source node initiates a route discovery process and the IERP is assigned to accomplish this task. To avoid large-scaled dissemination of routing request messages ZRP employs a third protocol, the `Bordercast Resolution Protocol` (BRP) [Haas, Z.J., Pearlman, M.R. and Samar, P. 2003], which is a sub-layer of the IERP protocol. The BRP identifies the nodes that are located in the source node's zone perimeter and forwards the route request messages only to those peripheral nodes. Figure 24 shows the route discovery process from node 10 to node 8 for an intra zone, $radius = 2$

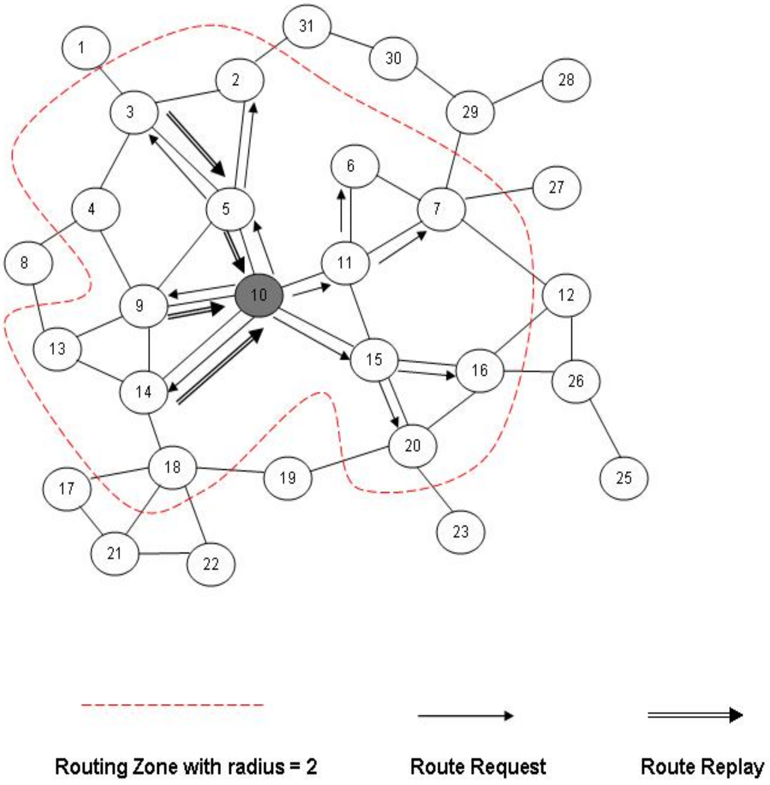


Figure 24. Route Discovery in ZRP

As node 8 is located outside the node 10 intra-zone, the BRP underlying protocol border-casts the RREQ messages to the peripheral nodes 2, 3, 4, 6, 7, 13, 16, 18, and 20. However, as nodes 3, 4, 9, and 14 already have a route to node 8, they initiate a RREP message without further forwarding the RREQ message. When node 10 receives multiple routes to the same destination, it stores the routes in its routing table and selects the shortest one, based on the number of hops. We observe in the Figure 24 that there is a possibility of collisions when multiple nodes transmit the RREP messages back to the source. However, the border-casting scheme minimizes the propagation of RREQ messages within a small region, except when the source/destination pair is located at opposite edges of the network. When a peripheral node does not have a route to the destination node, it originates a RREQ message and border-casts the message to its peripheral nodes. That procedure continues until a route to the destination is found.

Route maintenance takes place when a node in an active route detects a link failure in the route: the node employs a local reconfiguration of the path by searching for an alternate route to the destination. If such a route exists, the node originates an update message to inform all other nodes in the path and the source node of a change in the path. The source node may continue sending data packets in the new non-optimized route. If the source node wants to obtain a new optimal route, it regenerates a RREQ message, as previously discussed.

c. Security

ZRP does not employ any security mechanisms to ensure secure routing. However, any security mechanisms that have been proposed for other routing protocols can be applied to ZRP as well. Every node in the network can be in a promiscuous mode, overhearing transmissions from its neighbors and gathering statistical data on its neighbors' behavior. Again, in this case, there is a trade-off between processing time, latency, and security.

d. Conclusions

ZRP seems to employ the best characteristics of both reactive and proactive protocols. It avoids flooding the network with large-scaled Route Request messages, as reactive protocols do, and the periodic exchange of HELLO messages in the proactive scheme. Thus, ZRP reduces routing overhead in an inexpensive way. The only visible drawback of the protocol is, perhaps, that its performance depends heavily on the zone radius. For tactical communications, however, the zone radius can be set up in advance, before the establishment of the network, as we know priory the data traffic, the estimated velocity of the nodes, and the number of the nodes in the network. By optimizing the zone radius, we can succeed in the high performance of the protocol, or at least a better performance than any other "pure" proactive or reactive protocol.

2. Greedy Perimeter Stateless Routing (GPSR)

a. Protocol Overview

Greedy Perimeter Stateless Routing [Carp and Kung 2000] is a hybrid protocol whose functionality depends on knowledge of the geographic location of the nodes in network. That knowledge can be obtained by integrating a GPS device into the communication device or by other available means. Every node in the network must know its own location and the location of its neighboring nodes. Thus, every node periodically broadcasts its address and its location in *x* and *y* coordinates to all of its neighboring nodes. Data-packet forwarding decisions are based on the locations of both the source and the destination node. An address-to-location look-up algorithm is implemented to map a node address to its location.

A periodic exchange of beacons, which encapsulate the node address and location, is similar to the behavior of proactive protocols. The absence of any periodic route table information is closer to the philosophy of reactive protocols.

GPSR employs two algorithms to forward data packets from a source to a destination node: the greedy forwarding algorithm and the perimeter forwarding, algorithm that will be explained in the section b. The objective of the protocol's design is to minimize routing overhead and increase the packet delivery ratio in a network, by effectively responding to network topology changes without the dissemination of large-scaled control messages.

Finally, GPSR makes use only of bidirectional links between a node and its neighbors and does not support hierarchical routing.

b. Greedy and Perimeter Forwarding

In most cases, GPSR uses greedy forwarding for data packet delivery from a source or any intermediate node to the next node. The greedy forwarding algorithm needs to know the locations of a node's neighbors and the location of the destination node. According to this algorithm, the next-hop decision is based on the distance between the next node and the destination node. Each node forwards data packets to the next node that has the shortest distance to the destination node amongst other nodes in the node's "neighborhood". We define a node's "neighborhood" as the nodes within transmission range of a node. Figure 25 shows greedy forwarding in GPSR. The curved doted lines denote a node's transmission range.

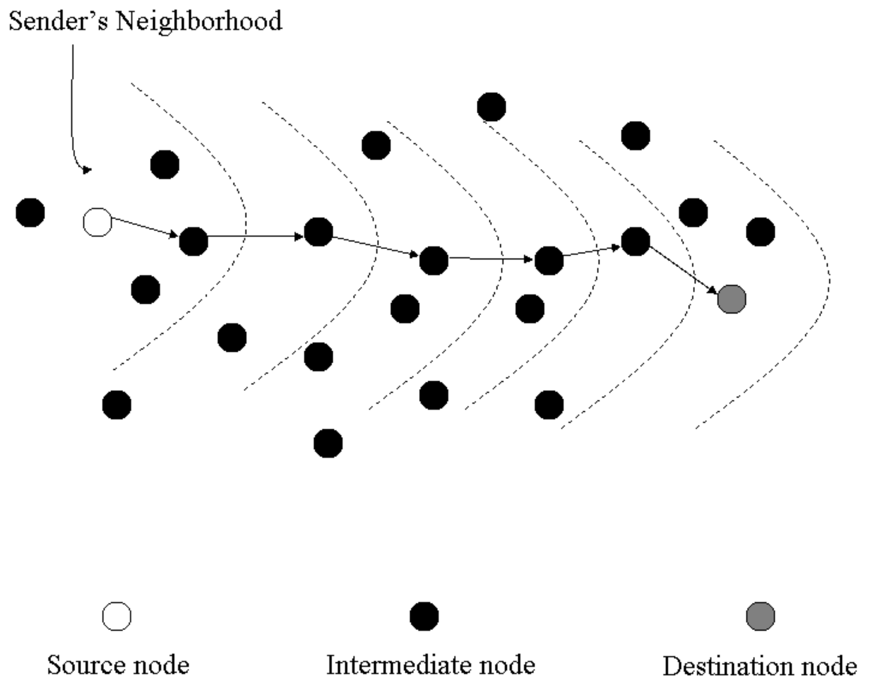


Figure 25. Greedy Forwarding in GPSR

However, greedy forwarding does not cover a case in which the distance between an intermediate node and the destination is the lowest as compared to distances from the intermediate node's neighbors and the destination node. Figure 26 shows a case in which the distance between node 4 and the destination node is the lowest compared to the distances between node 5 and node 6 and the destination node. In this case, GPSR employs "perimeter forwarding" in which node 4 stamps the data packet with a flag, to indicate that the packet enters into perimeter forwarding, and forwards the data packet to node 5 based on the "right hand rule".

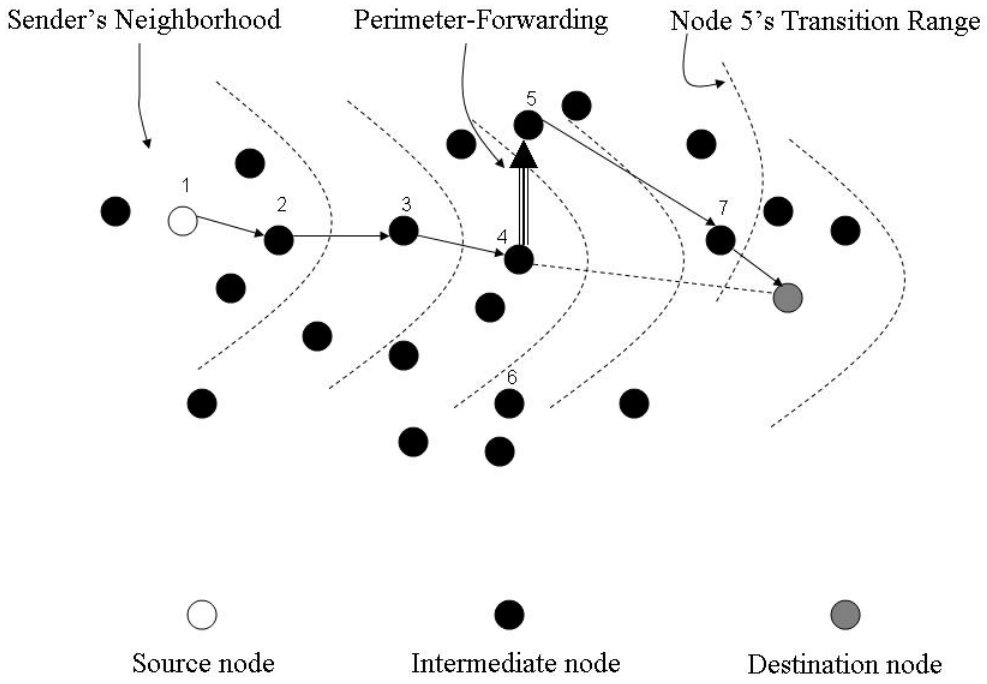


Figure 26. Perimeter Routing in GPSR

If a forwarding node (node 5 in Fig.26) has a neighbor (node 7 in Fig. 26) with a shorter distance to the destination node, the forwarding node (5) removes the "perimeter forwarding" flag, enters into "greedy forwarding", and forwards the data packet to the shorter-distance neighbor (7). The shorter-distance neighbor then uses greedy forwarding to forward the data packet to the destination.

However, there is always a possibility in mobile wireless networks that a destination node will be unreachable by any other node in the network. In that case, the data packet travels around the perimeter trying to find a path to the destination. If a path does not exist, the perimeter-forwarding algorithm never allows the packet to travel twice across the same link in the same direction. If a node "sees" that the only possible way to forward a data packet is to use a previous link toward the same direction, it drops the packet. This function ensures the loop-free behavior of the protocol.

c. Security

GPSR does not address any security vulnerabilities that exist in a mobile wireless network. Any attack on the location-finding algorithm will have severe consequences for the protocol’s performance because the proper behavior of the protocol is built on its knowledge of the location of destination nodes.

d. Conclusions

GPSR presents certain advantages over other protocols we have studied. First, it does not use any type of control messages, such as route requests and error messages. Second, it does not flood the network with any other type of control messages, except those between a node and its neighbors, for location-finding purposes. Using simulation results, B. Karp [2000] showed that GPSR outperforms even DSR, which is known as a protocol with very low routing overhead in a network of up to 200 nodes’ compared to other routing protocols, in terms of packet delivery ratio and routing overhead.

Perhaps the only visible drawback of GPSR is its dependence on “external” devices, such as GPS, that increase the implementation cost. For tactical implementation, this cost may be affordable; but we are not sure about commercial implementation. The presence of a GPS device introduces another drawback if it does not provide accurate node-location information. Any malfunction of the GPS device will degrade the protocol’s performance and may lead to network crash.

3. Comparison of Hybrid Protocols Based on Qualitative Metrics

Both ZRP and GPSR are loop-free protocols. ZRP ensures loop-free “behavior” by employing loop-free protocols inside inter and intra-zones. On the other hand, GPSR’s perimeter-forwarding algorithm never allows a packet to travel twice across the same link toward the same direction.

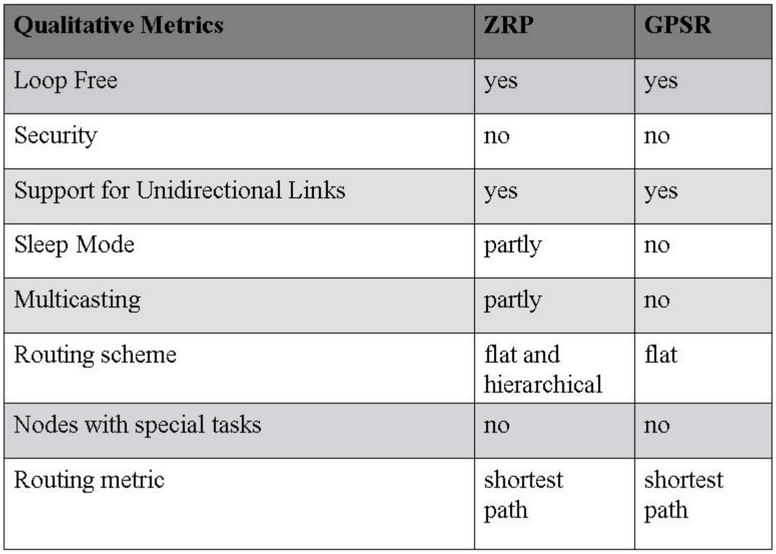
ZRP’s proactive behavior is more obvious than that of GPSR, in which nodes broadcast periodic beacons to their neighbors for location-update purposes. ZRP seems to present higher routing overhead depending on the zone radius. ZRP behaves like any other proactive protocol for the large value of this radius. However, one can optimize the value of the zone radius to meet the needs of the wireless network. If low latency is the main concern, reflecting lower data rates, the zone radius value should be high at least a $zone\_radius > 1$.

None of the above protocols addresses the security vulnerabilities of wireless networks. A possible solution is again monitoring the behavior of the nodes in the network, or employing security mechanisms at the link or physical Layers. GPSR seems to be more vulnerable than ZRP, as GPRS functionality is built on accurate location advertisements by the nodes in the network. Any malfunction of the GPS devices will degrade the protocol's performance.

Only ZRP provides support for unidirectional links, hierarchical routing, and interconnection with other non-ZRP routing domains. These are important attributes for a routing protocol for MANETs as they provide the means for extending an existing network with MANET technology, or interconnecting a MANET with other mobile and fixed networks.

As for the "sleep mode" operation, none of these protocols directly supports such an operation. The ZRP ''sleep mode" depends on the routing protocols that operate in the intra and inter zones. If OLSR is the routing protocol for the intra-zones, then ZRP can at least partially support this mode.

GPSR does not support multicasting. Routing decisions are solely based on the location of the destination node. On the other hand, ZRP depends on the "underlying" routing protocols within the inter and intra-zones. If AODV is used as the routing protocol for the inter-zones, it can provide multicasting support. Table 3 summarizes the performance of the above protocols, based on qualitative metrics.



Qualitative Metrics	ZRP	GPSR
Loop Free	yes	yes
Security	no	no
Support for Unidirectional Links	yes	yes
Sleep Mode	partly	no
Multicasting	partly	no
Routing scheme	flat and hierarchical	flat
Nodes with special tasks	no	no
Routing metric	shortest path	shortest path

Table 3. Comparison of Hybrid Protocols

Given the above metrics and the attributes of the two protocols, we suggest that ZRP would be a good candidate protocol in tactical mobile ad-hoc networks. Although GPS devices may be supplied in the battlefield to each individual node, we do not wish to base our communications structure on a variety of devices that increase the probability of malfunctions and network failure. A promising attribute of ZRP is the optimization of the zone radius to meet communication requirements. Hierarchical routing can reduce the size of routing tables and offer better scalability in the network. However, the source code [ZRP code] for ns-2 does not employ any optimization for protocol performance making any comparison with other protocols meaningless.

III. SIMULATION

A. ROUTING PROTOCOLS CHOSEN FOR SIMULATION

After the study and the evaluation of the routing protocols, based on qualitative metrics in accordance with the RFC 2501, three routing protocols were chosen for simulation and further evaluation in this thesis: OLSR, AODV and DSR.

B. SIMULATION SOFTWARE

1. The Network Simulator ns-2

The network simulator ns-2 [NS-2] is discrete event simulation software for network simulations. Ns-2 began as a variant of the REAL network simulator [REAL Network Simulator] in 1989. The latest version, ns-allinone-2.28, supports simulation for four routing protocols for ad-hoc wireless networks such as AODV, TORA, DSDV, and DSR. Ns-2 is written in C++ programming language and Object Tool Common Language (OTCL). Although ns-2 can be built on various platforms, we chose a Linux platform [FEDORA] for this thesis, as Linux offers a number of programming development tools that can be used along with the simulation process.

To run a simulation with ns-2, the user must write the simulation script in OTCL, get the simulation results in an output trace file, and analyze the results by using the *awk* command, Perl scripts, or any other trace analysis available program. A sample simulation script written in OTCL is shown in Appendix A. An output trace file is shown in Appendix B. For this thesis, we developed our own program written in Java programming language to analyze the ns-2 trace files and to calculate the four quantitative metrics that we use for the evaluation of the tested routing protocols. Ns-2 also offers a visual representation of the simulated network by tracing nodes' movements and events and writing them in a network animator (NAM) file.

However, ns-2, an open software that has been built by a number of different developers, suffers from a number of known and unknown bugs.

2. OLSR Routing Agent

To install the OLSR protocol we obtained a copy of the source code from the University of Murcia [UM-OLSR]. We recompiled and tested ns-2. The source code complies with RFC 3626 but does not support the use of multiple interfaces as they are defined in RFC 3626. OLSR multiple interfaces enable a mobile node to belong to different routing domains. However, in our simulations, mobile nodes belong to the same routing domain. OLSR code allows the user to define in the OTCL script the following parameters for protocol performance optimization:

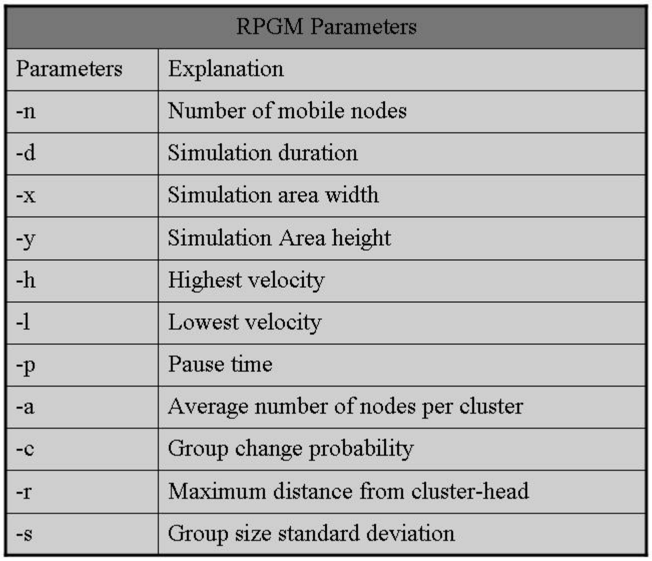
- Willingness: the willingness of a node to act as multipoint relay,
- A hello interval: the time interval between two HELLO messages, and
- A TC messages interval: the time interval between two TC messages.

By default, the values for node willingness, hello interval, and TC interval are 3, 2, and 5, respectively, in accordance with RFC 3626.

C. MOBILITY AND TRAFFIC SCENARIOS

1. Reference Point Group Mobility model (RPGM)

Ns-2 requires node movements to either be defined in the OTCL script or to be read from an external file. In this thesis, we used the Bonnmotion-1.3 software [Wall 2003], developed at the University of Bonn, to create mobile-node movement scenarios. The RPGM [Hong 1999] is a mobility model in which mobile nodes move in clusters in the simulation area. This model can create movements similar to military movements as army troops move mainly by forming clusters. The movement of cluster-heads is randomly chosen, and the movements of the cluster-members follow the direction of the cluster-head. The type of parameters that can be used for the generation of the RPGM mobility scenario is explained in Table 4.



RPGM Parameters	
Parameters	Explanation
-n	Number of mobile nodes
-d	Simulation duration
-x	Simulation area width
-y	Simulation Area height
-h	Highest velocity
-l	Lowest velocity
-p	Pause time
-a	Average number of nodes per cluster
-c	Group change probability
-r	Maximum distance from cluster-head
-s	Group size standard deviation

Table 4. RPGM parameters in Bonnmotion-1.3

To generate a reference-point-group-mobile scenario, the user should write the following command:

```
./bm –f scenario1 RPGM –n 50 –d 100 –x 2000 –y 1000 –h 10.0 –l 3.0 –p 3.0 –a 3.0 –c 0.03 –r 170 –s 1.0
```

After the generation of *scenario1*, the user should type the following command to transform *scenario1* into a file that can be read by ns-2:

```
./bm NSFile –f scenario1
```

Figure 27 shows the creation of clusters as it is shown in the NAM console after the end of the simulation.

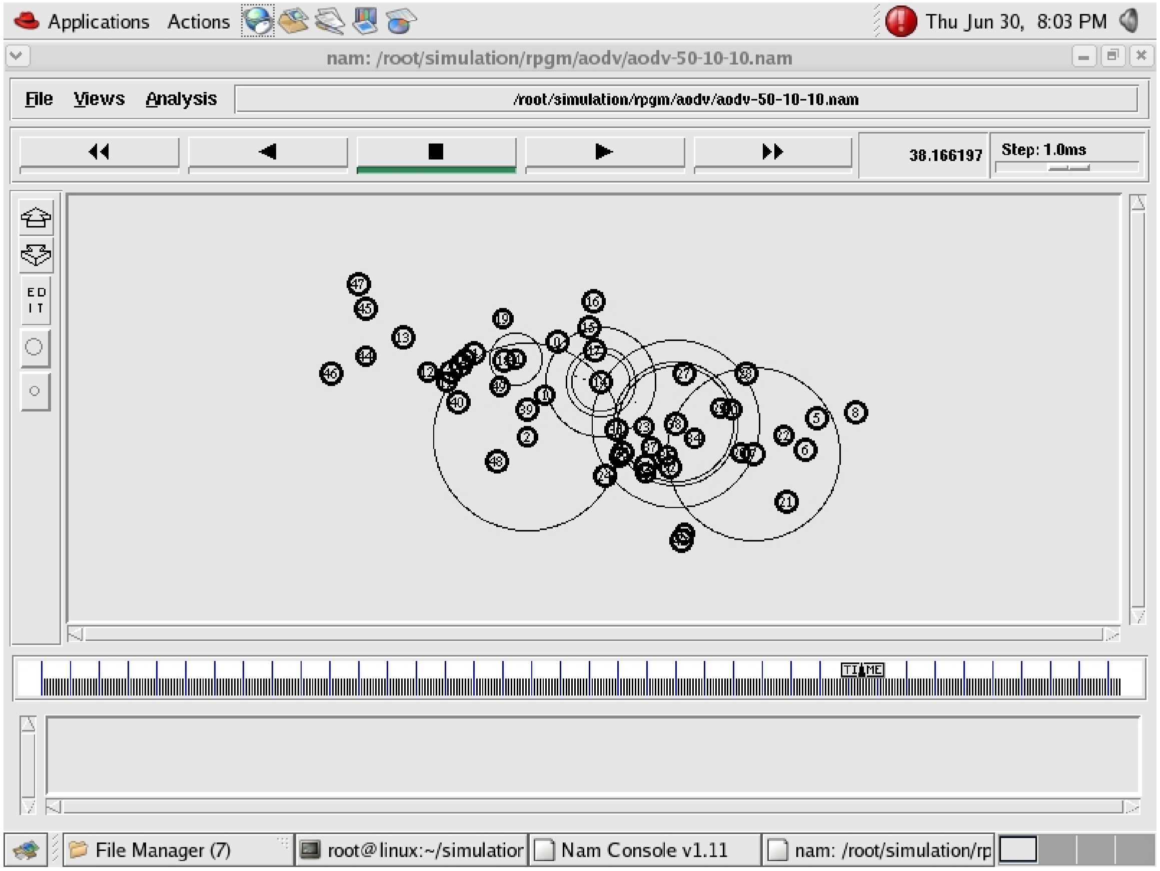
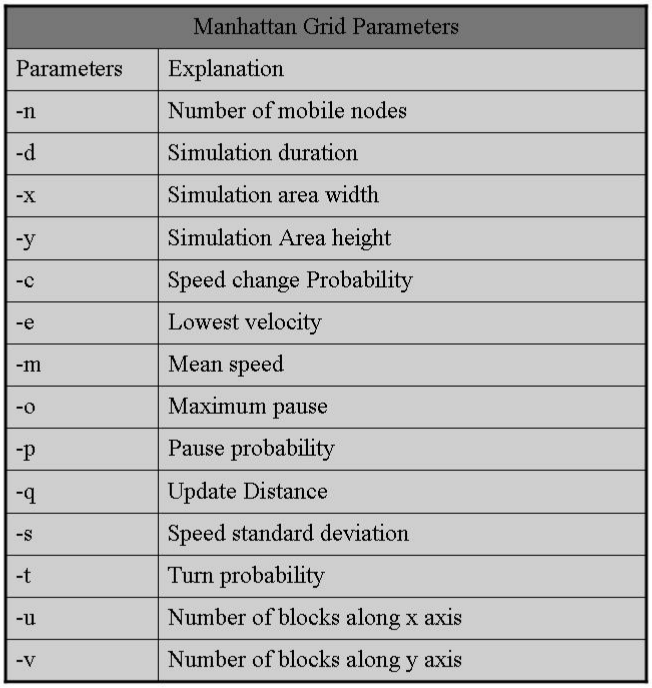


Figure 27. Creation of Clusters with the RPGM model

2. Manhattan Grid Mobility Model

In this model, nodes move in predefined paths. By using Bonnmotion-1.3, we can define the number of blocks along the x-axis and the y-axis, which will enable us to define the size of blocks in a city. This is an important attribute of the model because it enables us to create a scenario applicable to a specific targeted city in which mobile nodes move. The type of parameters that can be used for the generation of the Manhattan Grid mobility model is explained in Table 5.



Manhattan Grid Parameters	
Parameters	Explanation
-n	Number of mobile nodes
-d	Simulation duration
-x	Simulation area width
-y	Simulation Area height
-c	Speed change Probability
-e	Lowest velocity
-m	Mean speed
-o	Maximum pause
-p	Pause probability
-q	Update Distance
-s	Speed standard deviation
-t	Turn probability
-u	Number of blocks along x axis
-v	Number of blocks along y axis

Table 5. Manhattan Grid Model parameters in Bonnmotion-1.3

Figure 28 shows a screenshot of the NAM console at the end of the simulation with that mobility model. What is important in that model is that nodes at opposite sides of a block cannot communicate due to the reception failure posed by the blocks. As we increase the size of blocks in the simulation area, the probability of data packet loss by the mobile nodes increases.

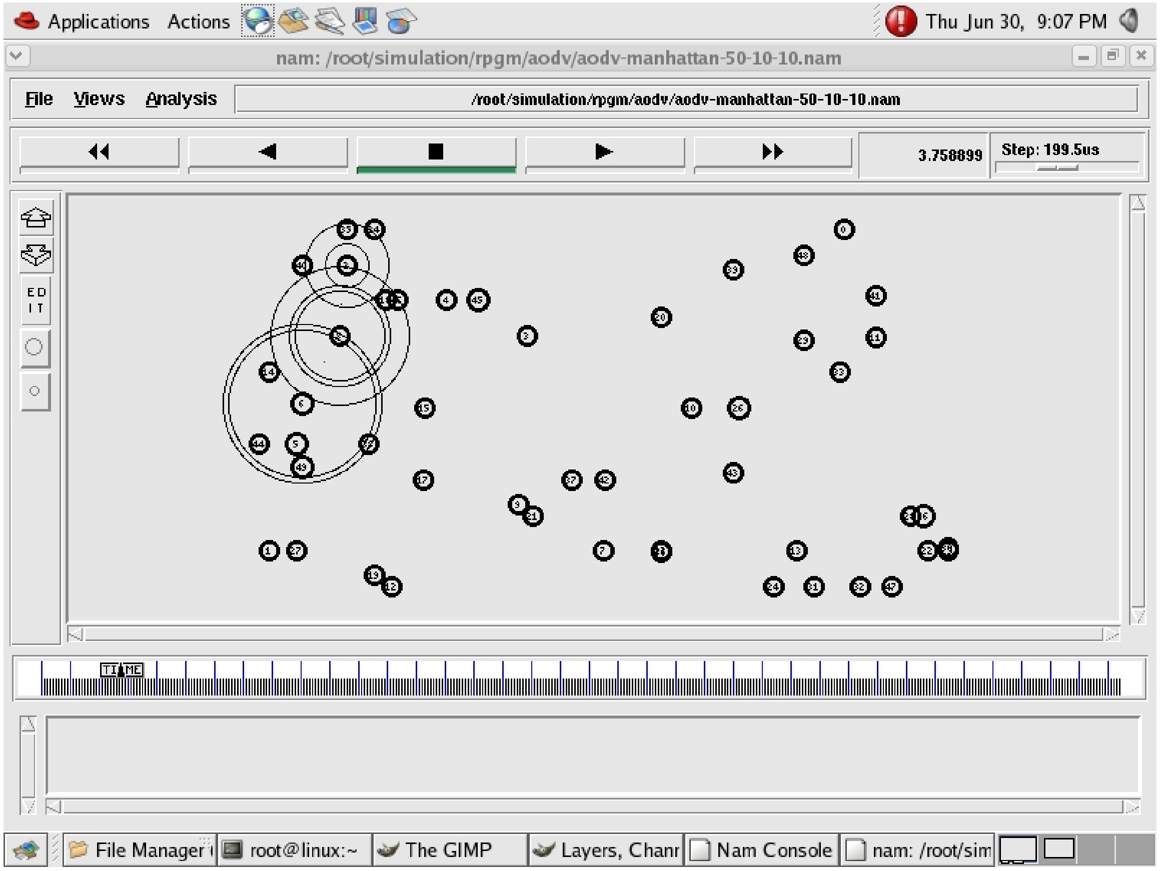


Figure 28. Manhattan Grid Mobility Model

3. Traffic Scenarios

NS-2 supports two different types of traffic for wireless ad-hoc networks. The user can choose either the Transmission Control protocol (TCP) or Constant Bit Rate (CBR). The traffic generator is located under the directory *indep-utils/cmu-scen-gen* and the two *tcl* scripts *tcpgen.tcl* and *cbrgen.tcl*, can be used for traffic generation. In this thesis, we used CBR as our traffic pattern. To create CBR connections the user should run

```
ns cbrgen.tcl –type cbr –nn 50 –seed 1.0 –mc 20 –rate 10.0 > cbr-outfile
```

where: -*type*, is cbr or tcp,

-*nn*, is the number of mobile nodes,

-*seed*, is a random seed,

-*mc,* is the maximum number of connections,

-*rate,* is the number of packets per second.

The start times for the CBR connections are randomly chosen with a maximum time value set to 180 sec. The user can change the start times in the cbr-outfile to keep them within the limits of the simulation time. A sample cbr-outfile is shown in Appendix C.

D. QUANTITATIVE METRICS

1. Introduction

RFC 2501 describes a number of quantitative metrics that can be used for evaluating the performance of a routing protocol for mobile wireless ad-hoc networks. In this thesis, we follow the general ideas described in RFC 2501, and we use four quantitative metrics similar to those that were used in [Das, S.R., Perkins, C.E. Royer, E.M. 2000]. The packet delivery ratio and average end-to-end delay are most important for best-effort traffic. The normalized routing load will be used to evaluate the efficiency of the routing protocol. Finally, the normalized MAC load is a measure of the effective utilization of the wireless medium for data traffic. In the next sections, we will define those four quantitative metrics.

2. Packet Delivery Ratio

The packet delivery ratio is defined as the fraction of all the received data packets at the destinations over the number of data packets sent by the sources. This is an important metric in networks. If the application uses TCP as the layer 2 protocol, high packet loss at the intermediate nodes will result in retransmissions by the sources that will result in network congestion.

$$Packet\_Delivery\_Ratio = \frac{Total\_Data\_packets\_received}{Total\_Data\_packets\_sent}$$

3. Average End-to-End Delay

End-to-end delay includes all possible delays in the network caused by route discovery latency, retransmission by the intermediate nodes, processing delay, queuing delay, and propagation delay. To average the end-to-end delay we add every delay for each successful data packet delivery and divide that sum by the number of successfully received data packets. This metric is important in delay sensitive applications such as video and voice transmission.

$$Average\_End2End\_Delay = \frac{\Sigma\left(Time\_received - Time\_sent\right)}{Total\_Data\_packets\_received}$$

4. Normalized Routing Load

The normalized routing load is defined as the fraction of all routing control packets sent by all nodes over the number of received data packets at the destination nodes. This metric discloses how efficient the routing protocol is. Proactive protocols are expected to have a higher normalized routing load than reactive ones. The bigger this fraction is the less efficient the protocol.

$$Normalized\_Routing\_Load = \frac{Total\_Routing\_packets\_sent}{Total\_Data\_packets\_r\mathrm{e}ceived}$$

5. Normalized MAC Load

The normalized MAC load is defined as the fraction of all control packets (routing control packets, Clear-To-Send (CTS), Request-To-Send (RTS), Address Resolution Protocol (ARP) requests and replies, and MAC ACKs) over the total number of successfully received data packets. This is the metric for evaluating the effective utilization of the wireless medium for data traffic.

$$Normalized\_MAC\_Load = \frac{Total\_Control\_packets\_sent}{Total\_Data\_packets\_received}$$

E. TRACE ANALYSIS SOFTWARE

This program analyzes the ns-2 trace files and calculates the values of the above four quantitative metrics. In the next section, we explain how to get those values from the ns-2 trace file.

Calculating Packet Delivery Ratio

In ns-2 trace files a data packet is delivered at the destination node only if there is a receive event with the same packet sequence number associated with the agent type AGT. We build two lists, one of received and one of sent CBR packets with the agent type AGT. For the *sentPktList,* we store values for transmission time and packet sequence number. In the same way, we store the receiving time and the sequence packet number in the *rcvPktList.* Two counters, named *rcvPkts* and *sentPkt,* are used to calculate the packet delivery ratio.

Calculating Average End-to-end delay

For every packet in the *sentPktList*, we search its sequence number in the *rcvPktLis* and store the transmission time. For each successful matching, we extract the receiving time of that packet and calculate the end-to-end delay. To find the average end-to-end delay we sum all the delays and divide by the number of *rcvPkts.*

Calculating Normalized Routing Load

We count all send events with agent type RTR and packet type any control packet that the routing protocol generates. To calculate the normalized routing load we divide the sum of all control routing packets by the number of *rcvPkts*.

Calculating Normalized MAC Load

We count all the send events with agent type MAC and packet type RTS, CTS, ARP, and ACK and add to this number the sum of all control routing packets found in the previous calculation. To calculate the normalized MAC load, we divide the sum of all control packets (MAC and routing control packets) by the number of *rcvPkts.*

The program is able to provide the wished results for any size of trace file in a few minutes and can be easily extended to include any routing protocol. The source code of the Trace Analysis program is shown in Appendix D.

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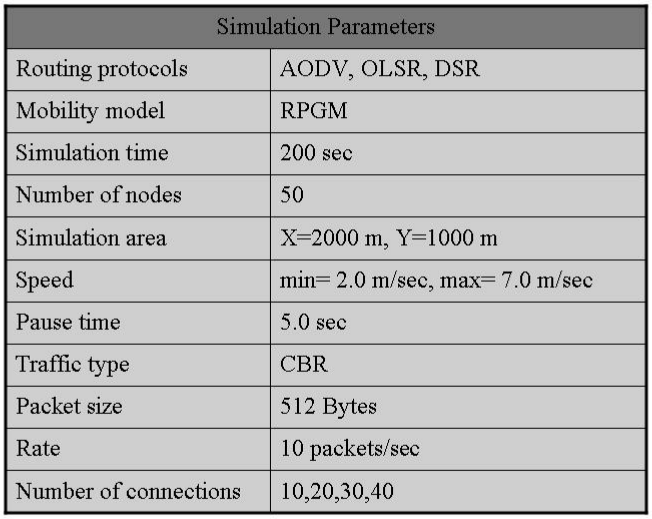
IV. SIMULATION RESULTS

A. REFERENCE POINT GROUP MOBILITY (RPGM) MODEL

1. Varying the Number of Connections

In the first set of simulations, we increase the number of connections from 10 to 40 and keep all other parameters unchanged. The data traffic and the routing load in the network increase as we increase the number of connections. We keep a constant bit rate of 10 packets/sec (40.960 Kbps) for all cases. Table 6 shows the parameters of the simulation.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
Speed	min= 2.0 m/sec, max= 7.0 m/sec
Pause time	5.0 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	10 packets/sec
Number of connections	10,20,30,40

Table 6. RPGM, Varying the Number of connections

With this low-to-medium traffic, the routing protocols are expected to have a high packet delivery ratio and a low normalized routing and MAC load. We expect OLSR to have a lower and-to-end delay than AODV and DSR due to its proactive behavior.

Figure 29 shows the packet delivery ratio of the protocols. We observe that all protocols have almost the same performance with AODV to present a higher packet delivery ratio in all cases. OLSR has the worst performance. The explanation is that, because nodes within the clusters are very close, data packets are dropped at the MAC layer. The reason being for that is that the network is congested at some point by the periodic transmission of HELLO messages and OLSR routing packets. Therefore, the existence of valid routes between a source/destination pair in a node's routing table, does not necessarily guarantee a better packet delivery ratio.

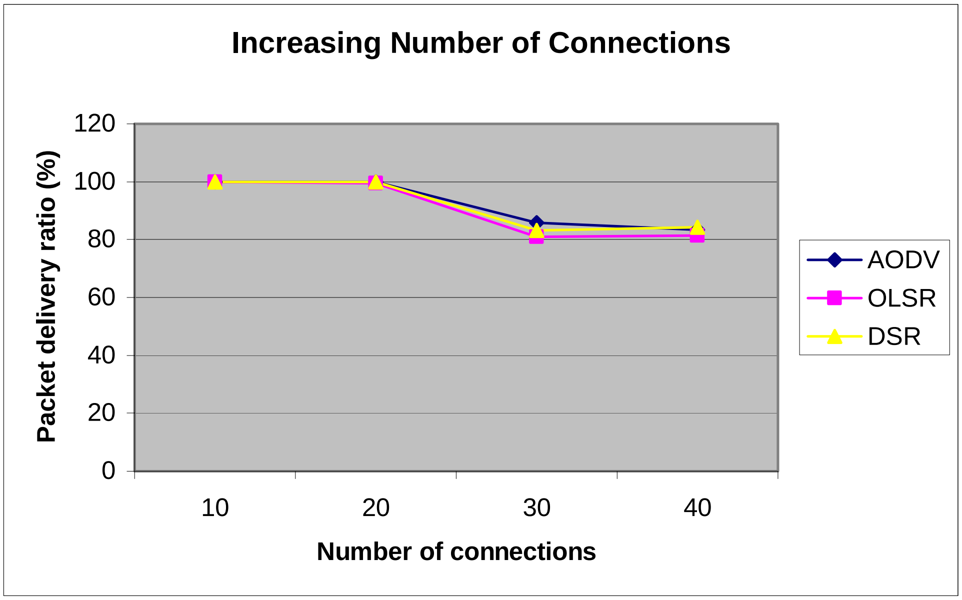


Figure 29. RPGM, Packet Delivery Ratio (Increasing number of connections)

Figure 30 shows the normalized routing load of the protocols. We observe that OLSR has a normalized routing load 800 percent higher than AODV and DSR for 10 connections. With a higher number of connections, OLSR "stabilizes" its routing overhead. This happens because, with a higher number of connections, the number of the received packets at the destinations is getting higher while the number of OLSR routing packets remains the same. As a result, the value of the normalized routing load fraction is getting higher. AODV presents a higher routing load than DSR for an increased number of connections, as nodes need to transmit a bigger number of routing control messages to establish and maintain those additional connections. DSR seems to be the most stable protocol regardless of the number of connections in the network due to its cashing mechanism at the source and intermediate nodes.

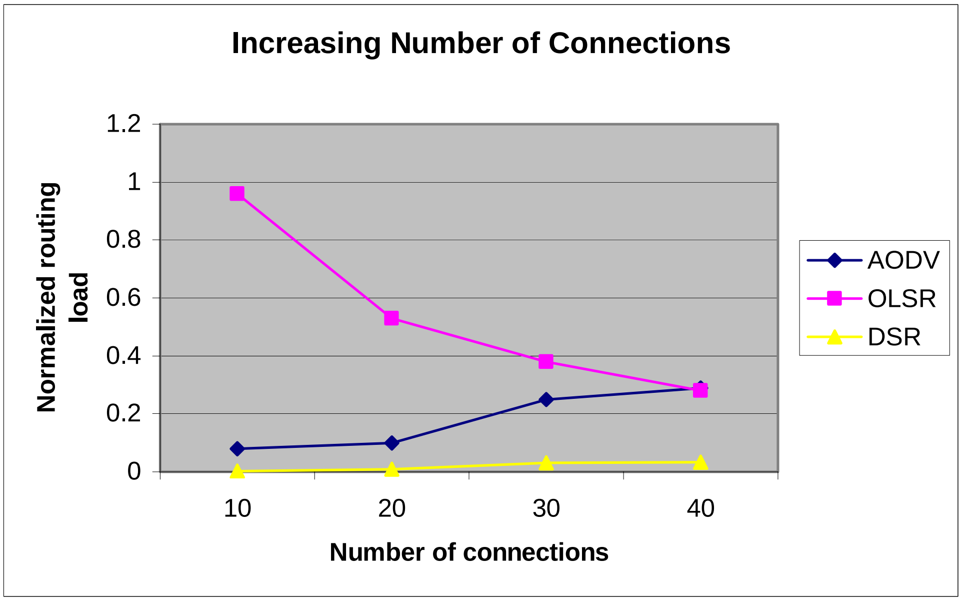


Figure 30. RPGM, Normalized Routing Load (Increasing number of connections)

Figure 31 shows the normalized MAC load of the protocols. We observe that OLSR has a higher MAC load than AODV and DSR for 10 and 20 connections. However, with 30 and 40 connections, OLSR presents the lowest MAC load.

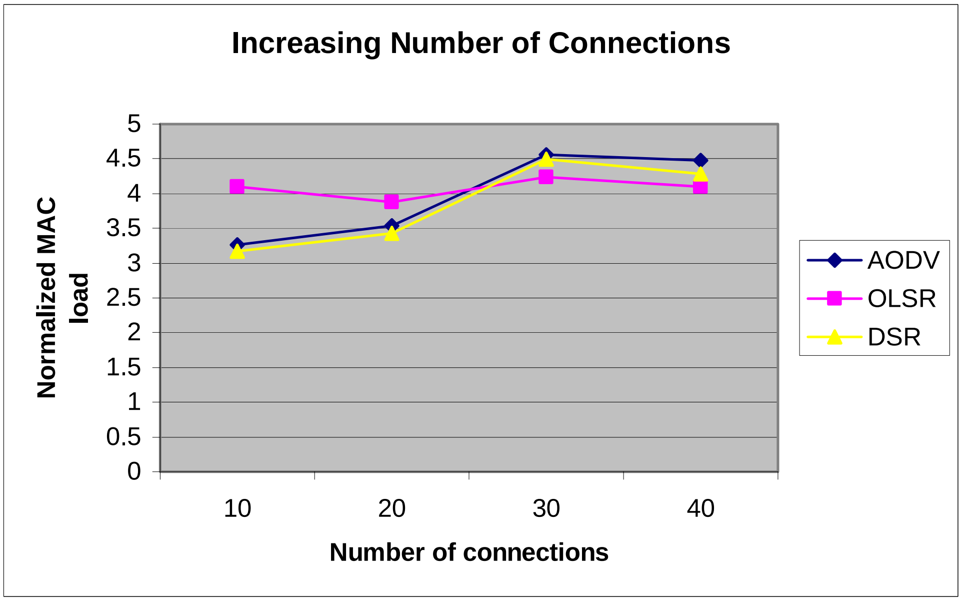


Figure 31. RPGM, Normalized MAC Load (Increasing number of connections)

The explanation is that both AODV and DSR generate a higher number of messages at the MAC layer because more control messages are needed to satisfy the establishment and maintenance of those new connections. The MAC layer generates

RTS, CTS, and ACK messages for each transmission of RREQ, RREP, and RERR messages. Thus the higher the number of routing control messages, the higher the normalized MAC load. On the other hand, OLSR generates those additional RTS, CTS, and ACK messages at the MAC layer only for data packets transmission, as the time interval for HELLO and other types of OLSR routing control packets remains unchanged, regardless of the increased number of connections. The conclusion is that, although AODV and DSR generate a lower number of routing control messages, the utilization of the wireless medium by data traffic is better in OLSR in a network in which the number of connections increases over time.

Finally, Figure 32 shows the average end-to-end delay of the protocols. OLSR has the lowest and-to-end delay, which increases almost linearly with the number of connections. DSR has lower end-to-end delay than AODV, although AODV employs a similar chasing mechanism to that of DSR. This is because the timeout value for erasing routes that has been used previously in AODV is not optimized to cover all possible mobility and traffic scenarios. We observe that DSR has higher end-to-end delays for 30 connections for the same reason.

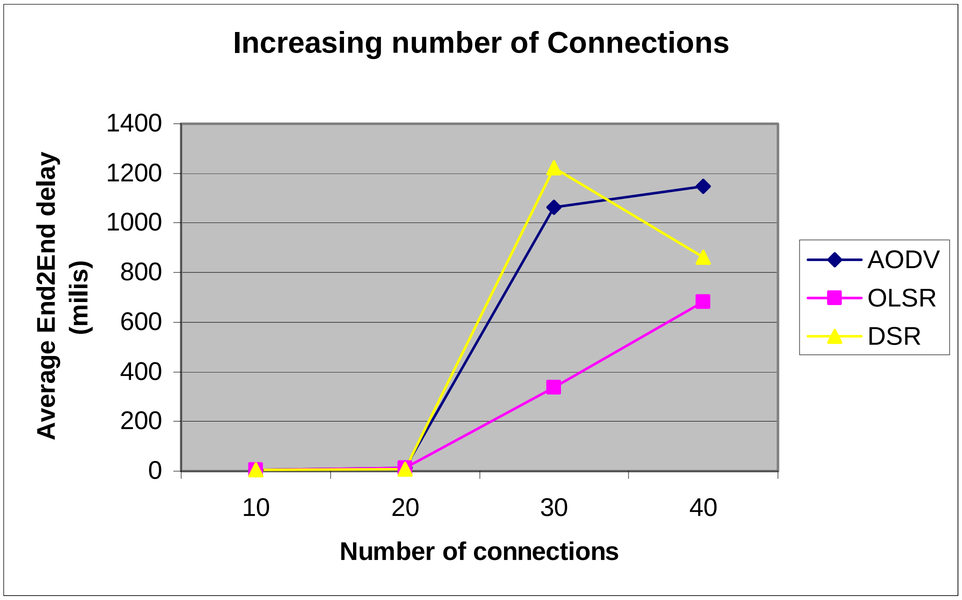
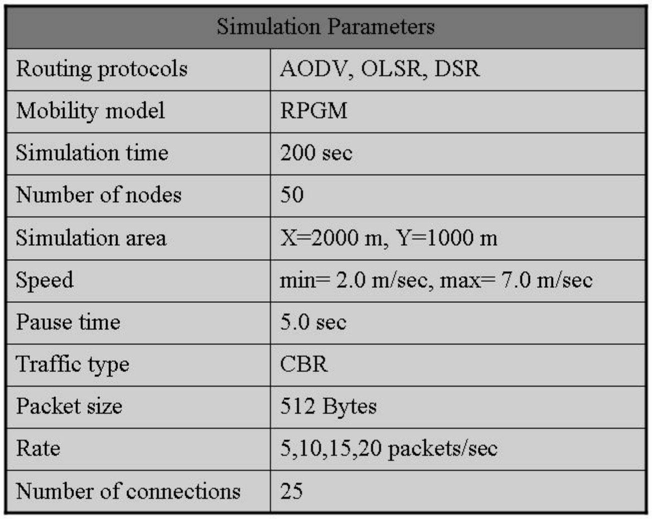


Figure 32.   RPGM, End2End Delay (Increasing number of connections)

2. Varying the Network Load

In the second set of simulations, we increase the number of data packets sent by the sources from 5 packets/sec (20.480 Kbps) to 20 packets/sec, (81.920 Kbps), keeping all other network parameters unchanged. The demand for efficient routing and wireless medium utilization for data traffic is higher in that scenario; we will observe how the three protocols can scale in that demanding network. We observed that, under that mobility scenario and a packet rate of more than 25 packets/sec (102.400 Kbps), all protocols present a very low packet delivery ratio (below 50 percent), making any comparison at those rates meaningless. Table 7 shows the parameters of the simulation.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
Speed	min= 2.0 m/sec, max= 7.0 m/sec
Pause time	5.0 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	5,10,15,20 packets/sec
Number of connections	25

Table 7. RPGM, Varying the Network load

Figure 33 shows the packet delivery ratio of the protocols. All protocols have an identical performance at low rates (5 packets/sec). DSR outperforms AODV and OLSR in all cases, whereas OLSR has, again, the worst performance. Although we placed 50 nodes in an area of 2000 x 1000 meters to avoid interference, nodes are still in close proximity, especially within the clusters. This scenario does not favor OLSR: we noticed by analyzing the ns-2 trace files that OLSR produces a fairly large size of route update packets that require higher transmission time than that of AODV and DSR. Neither

AODV nor DSR suffers from that periodic exchange of link state information, as routes are discovered in an ad-hoc fashion. By analyzing also the trace files, we observed that data packets are dropped by AODV for the following reason.

a) In AODV, the source node will send a RREQ message if a route to the destination node does not exist. After the second transmission of the RREQ message, if the source node does not receive a RREP message within a time interval, it will drop the first packet in the queue and repeat the same procedure for the second data packet in the queue. However, if any intermediate node cannot find a valid route to the destination node by repeating the above procedure, it will drop not only the first packet but also all data packets from its queue, thereby degrading the protocol's performance.

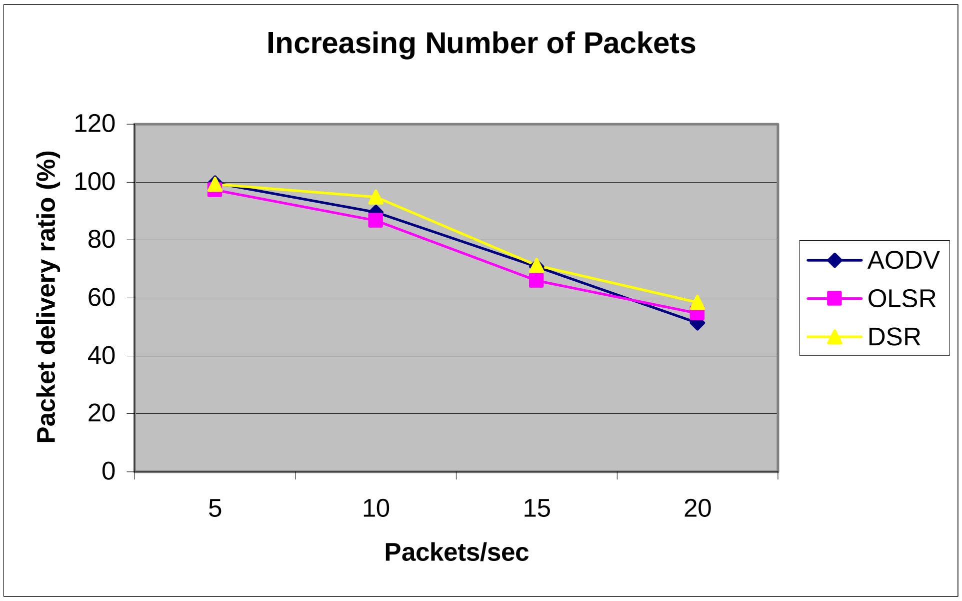


Figure 33. RPGM, Packet Delivery Ratio (Increasing number of packets)

Figure 34 shows the normalized routing load. DSR has the lowest routing load at all packet rates, showing that it scales well in networks with low mobility in which data traffic increases over time. OLSR has a high routing load in low traffic (5packets/sec), which drops significantly in higher traffic. AODV has a higher routing load than DSR, although, like DSR, it employs an expanding ring and cashing mechanism. However, AODV was designed for networks with a larger number of nodes and higher mobility than that in our simulation.

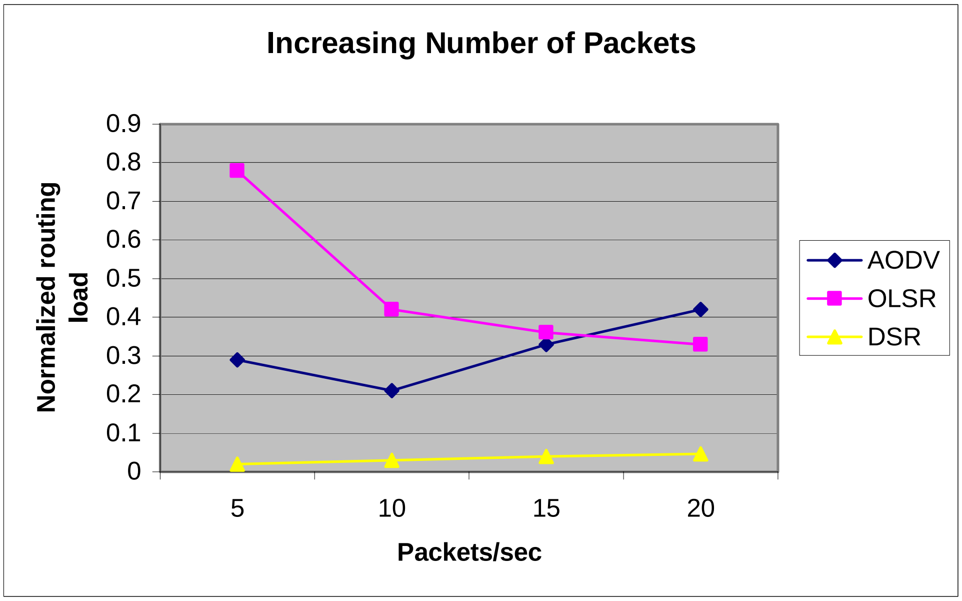


Figure 34. RPGM, Normalized Routing Load (Increasing number of packets)

Figure 35 shows the normalized MAC load. DSR has the best performance at all rates. We observe also that AODV has a higher MAC load than OLSR, although the AODV routing load is lower than that in OLSR. We explained in the previous section why that happens.

Figure 36 shows the end-to-end delay. We expected OSLR to have better performance than the other two reactive protocols. However, the end-to-end delay in OLSR increases when the data traffic increases. The explanation lies in the low mobility of the network. As nodes do not change their positions very frequently, there exists a high level of network congestion at certain regions of the network because none of the three protocols employs any mechanism for load balancing, data traffic is not evenly distributed in the network, and high end-to-end delays result.

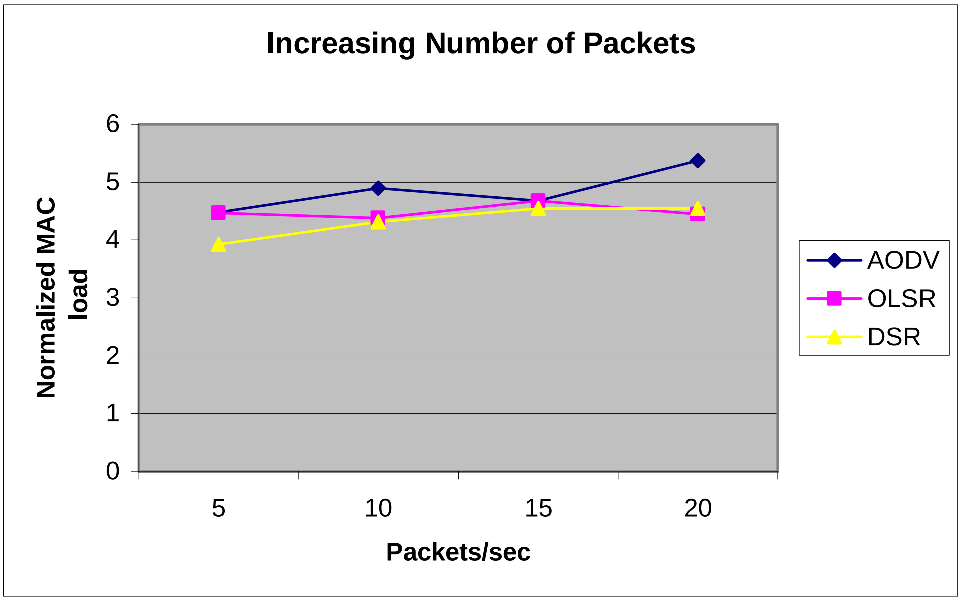


Figure 35. RPGM, Normalized MAC Load (Increasing number of packets)

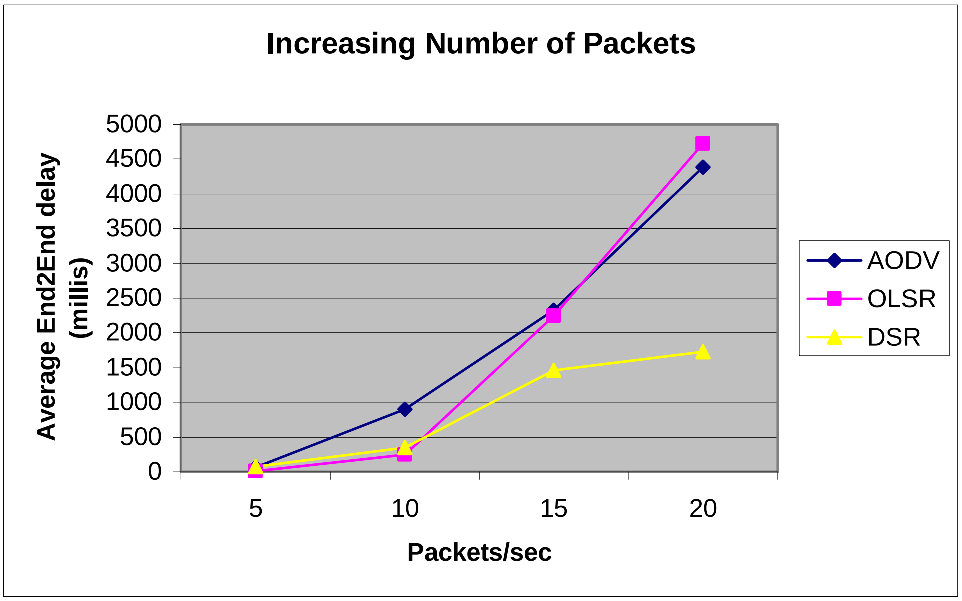
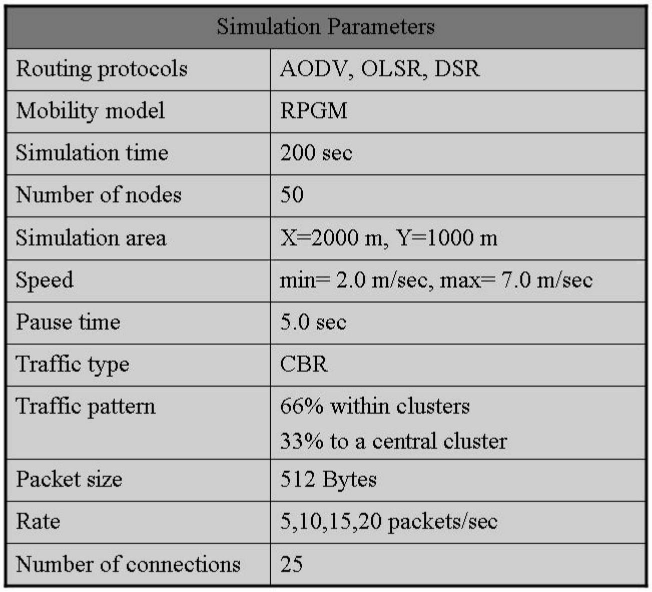


Figure 36. RPGM, End2End Delay (Increasing number of packets)

3. Distributing the Network Load

In the third set of simulations, we distribute the network load so that 66 percent of the data packets are destined within the clusters and 33 percent are destined to a cluster at a central position in the simulation area. We do that to approximate a real situation scenario in which a node within each cluster, which we arbitrarily choose to be the cluster head, communicates with its neighboring nodes within the cluster and with other nodes at a central position in the simulation area, which represents the Headquarters (HQ) of the unit. As none of the protocols employs a mechanism for balancing the network load, we expect all the protocols to have a lower performance than in our previous scenario. This is because nodes around the central cluster behave as “bottlenecks” of the network, dropping data packets. However, this is a real situation in tactical communications, and we wish to analyze the behavior of the tested protocols under that scenario. Table 8 shows the parameters of the simulation.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
Speed	min= 2.0 m/sec, max= 7.0 m/sec
Pause time	5.0 sec
Traffic type	CBR
Traffic pattern	66% within clusters 33% to a central cluster
Packet size	512 Bytes
Rate	5,10,15,20 packets/sec
Number of connections	25

Table 8. RPGM, Distributing the Network load

Figure 37 shows the packet delivery ratio. All protocols present almost identical performance, which is lower than in our previous scenario. That at least indicates that all three protocols can be used for any traffic scenario in a network with a low number of nodes, medium data traffic, and medium mobility.

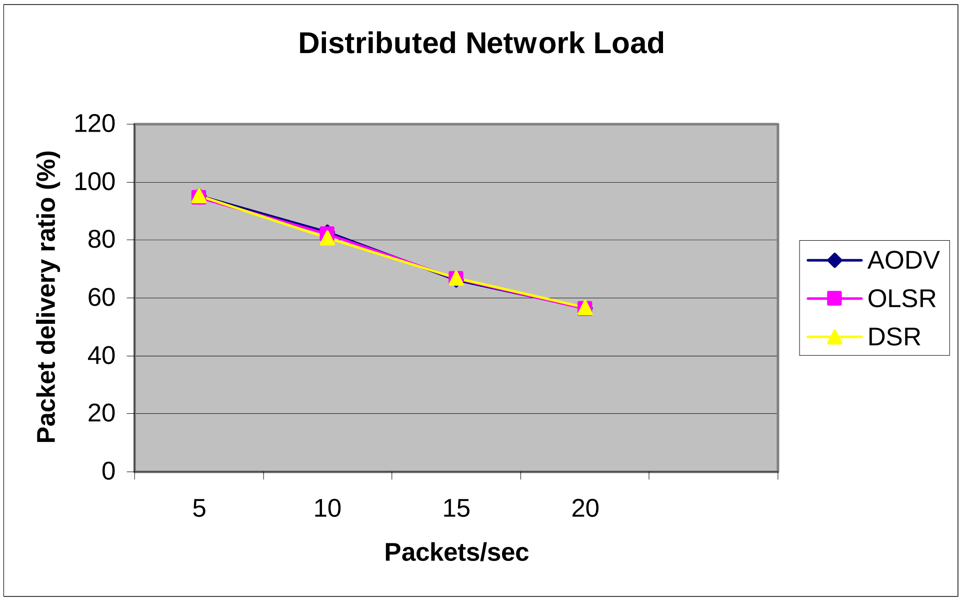


Figure 37. RPGM, Packet Delivery Ratio (Distributing the Network load)

Figure 38 shows the normalized routing load of the protocols. We observe that DSR has the lowest routing load that remains stable regardless of the data packet rate. AODV, in contrast, presents the highest routing load. We explained in the previous section that the reason for AODV's high routing load lies in the design of AODV, which performs better in larger networks with a higher mobility.

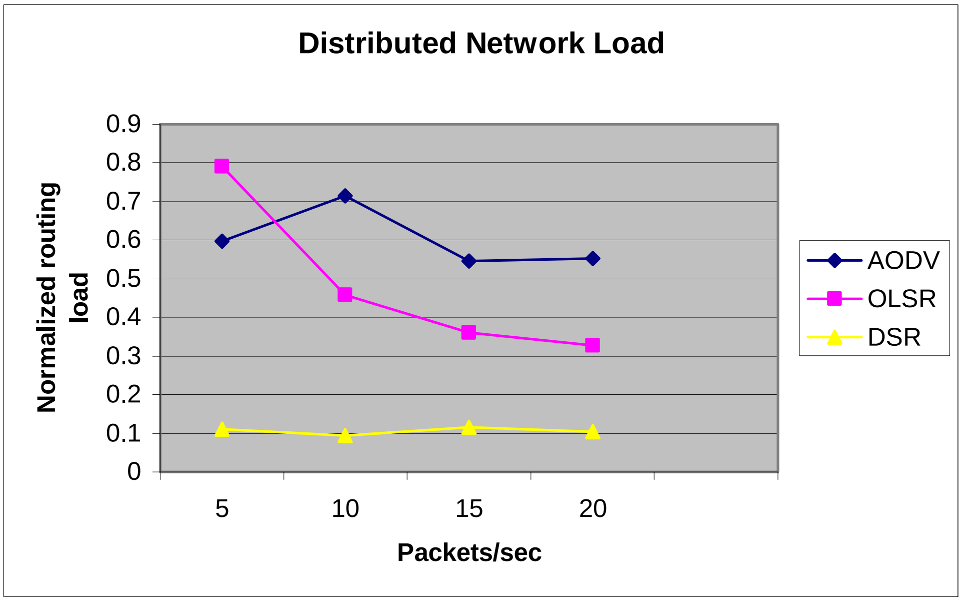


Figure 38. RPGM, Normalized Routing Load (Distributing the Network load)

Figure 39 shows the normalized MAC load. OLSR again presents the lowest MAC load, while the DSR performance is the most stable. AODV has the highest MAC load at lower data packet rates; that drops when the data packet rates increase.

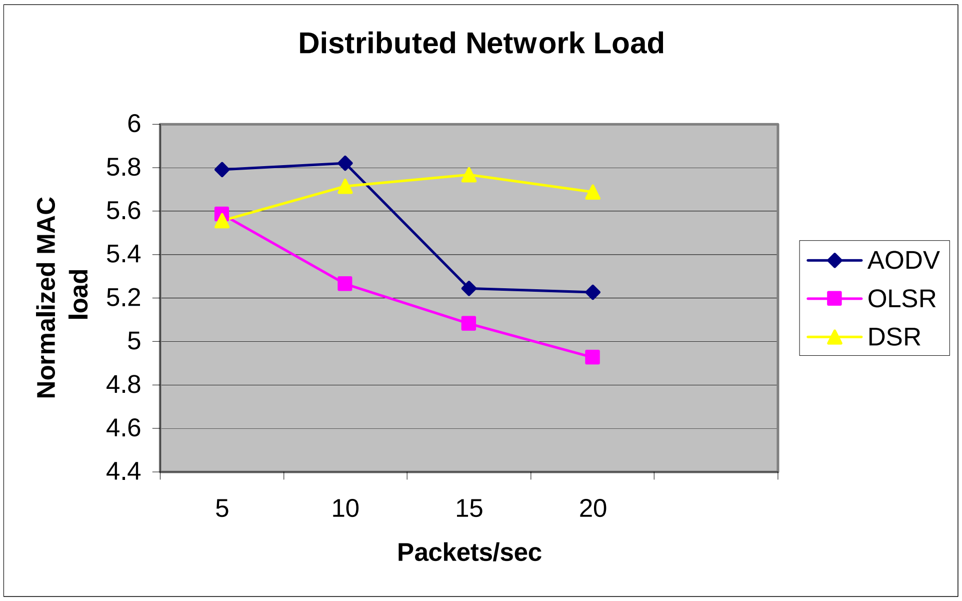


Figure 39. RPGM, Normalized MAC Load (Distributing the Network load)

Finally, figure 40 shows the average end-to-end delay of the protocols. OLSR has the lowest end-to-end delay at lower rates while DSR has the lowest end-to-end delay at higher rates.

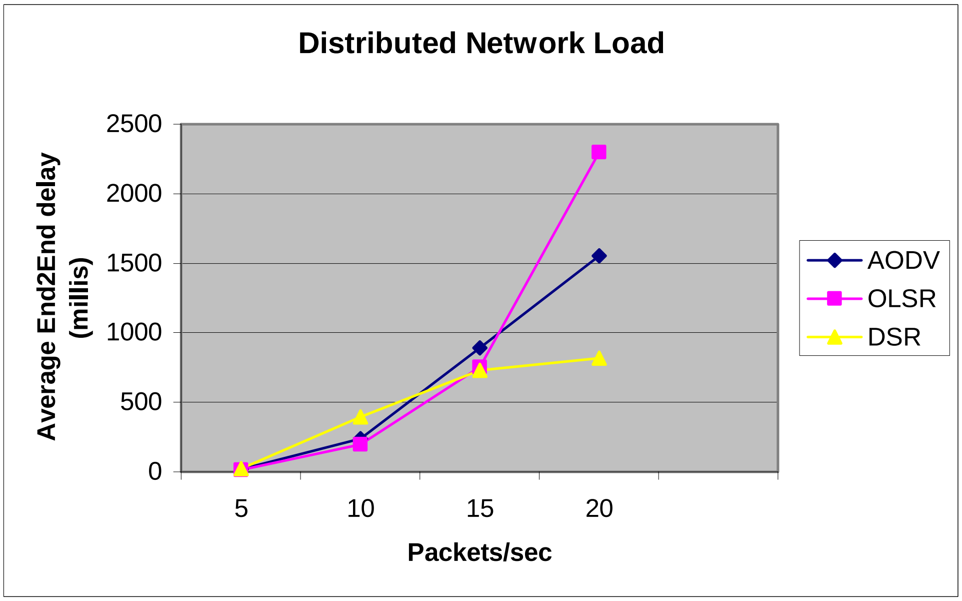


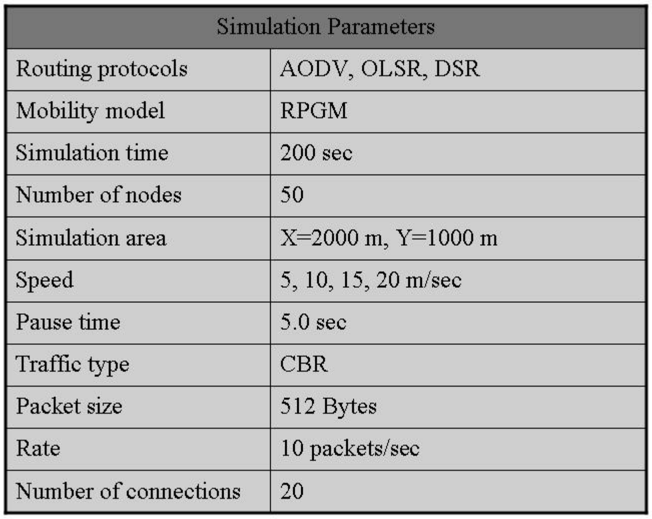
Figure 40. RPGM, End2End Delay (Distributing the Network load)

What is interesting in the above results is that OLSR presents the highest end-to-end delay at higher data packet rates. By analyzing the simulation trace files, we observed that the size of OLSR TC messages is within the range (48, 2020) bytes. Every 5 seconds all MPR nodes flood the network with TC messages. In our ns-2 implementation, we configured the node's interface queue in such a way that all routing control messages have the highest priority amongst other types of packets, so routing protocols can adapt the network changes in a timely manner. However, that size of TC messages in OLSR causes high end-to-end delay for data packets due to processing, transmission, and propagation delays at the intermediate nodes. In conclusion, the proactive attribute of a protocol does not necessarily guarantee a lower end-to-end delay. Routing control packets size, mobility, and data traffic all affect protocol performance, and, under scenarios, like in the one above, a proactive routing protocol may introduce higher end-to-end delay than a reactive routing protocol.

4. Varying Network Mobility

In the fourth set of simulations, we vary nodes' mobility. We start with a mobility scenario in which the nodes have a low velocity of 5 m/sec (18 Km/h). We then increase nodes' velocity up to 20 m/sec (72 Km/h). Our intention is to investigate the behavior of the three protocols in networks with varied mobility, although the high mobility, 72 Km/h, cannot be easily found in tactical movements.

We keep a constant data rate of 10 packets/sec (40.960 Kbps) and a constant number of 20 connections. We observed that, at higher data rates with increasing mobility, the performance of the protocols decreases due to network congestion in a way that makes any comparison meaningless. Table 9 shows the simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
Speed	5, 10, 15, 20 m/sec
Pause time	5.0 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	10 packets/sec
Number of connections	20

Table 9. RPGM, Varying Network Mobility

Figure 41 shows the packet delivery ratio of the protocols. All protocols, present a similar performance with AODV, having the best performance at all mobility rates. We observe again that protocols have a better performance when the speed of the nodes is 10 m/sec and 15 m/sec, because the network load is more evenly distributed among the nodes at higher mobility rates.

Figure 42 shows the normalized routing load. DSR has the best performance with an increase of the routing load at a higher mobility. That stable behavior of DSR is a desirable property of a protocol as it indicates that it can scale well in networks in which the mobility changes over time. OLSR has the same behavior, while the AODV performance increases when nodes move at higher speeds.

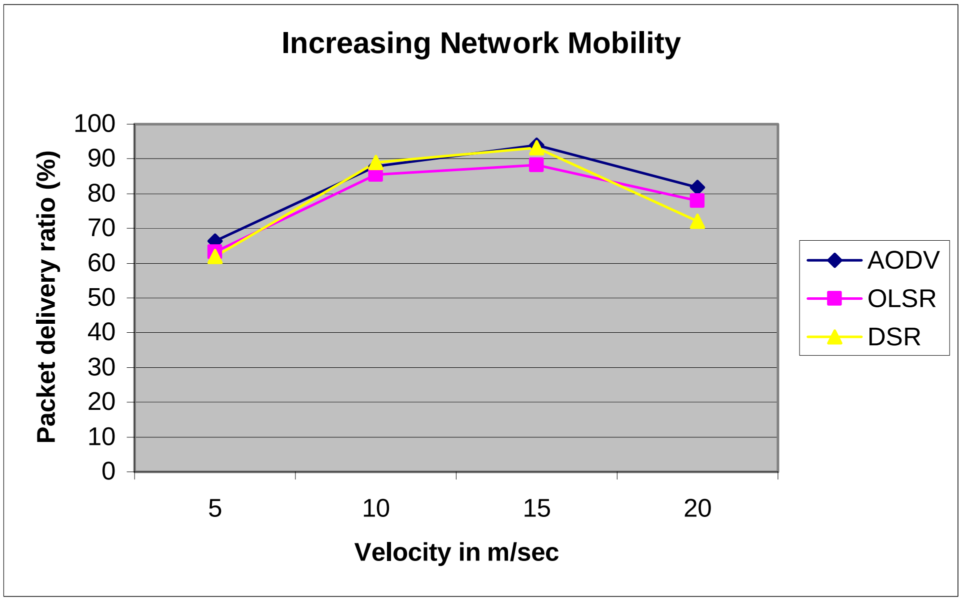


Figure 41. RPGM, Packet Delivery Ratio (Varying Network Mobility)

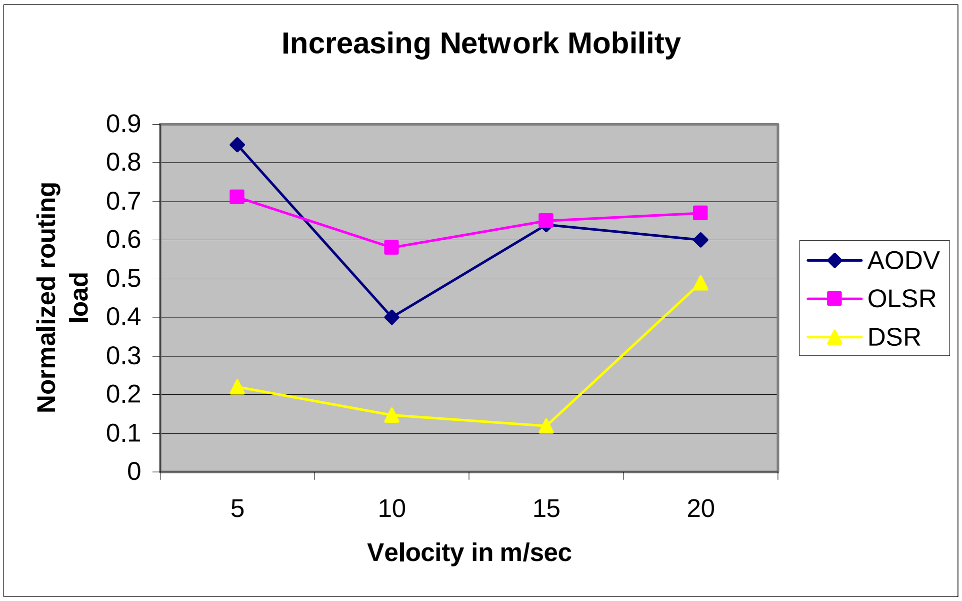


Figure 42. RPGM, Normalized Routing Load (Varying Network Mobility)

Figure 43 shows the normalized routing load. AODV has lower normalized MAC load than DSR, despite having a higher normalized routing load. The explanation is that under this simulation scenario, the route discovery in AODV is more accurate than in DSR. DSR, as a result, generates a higher number of routing control messages than

AODV to discover alternate routes at the intermediate nodes. OLSR is the most stable protocol in terms of the normalized MAC load in networks with varying mobility.

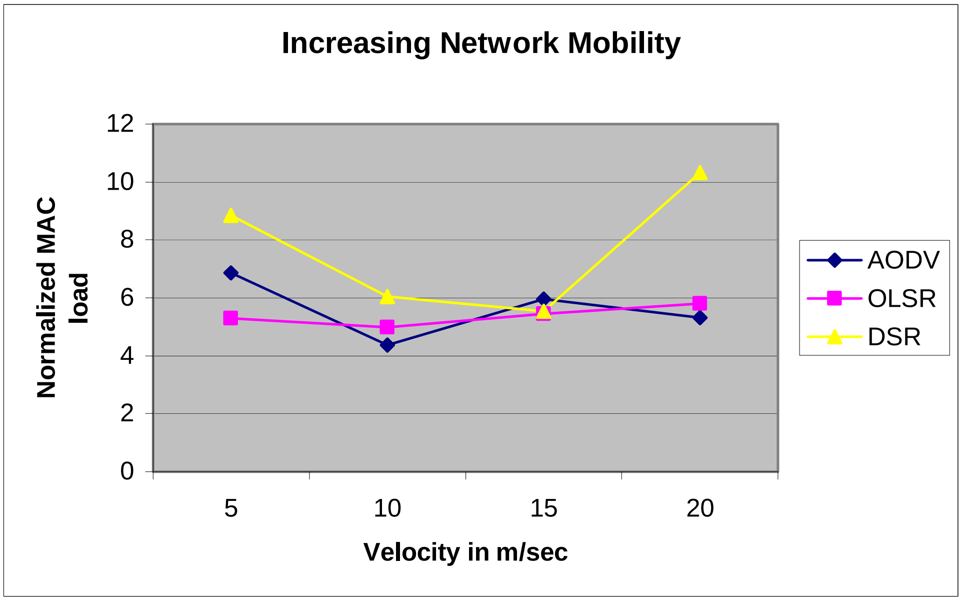


Figure 43. RPGM, Normalized MAC Load (Varying Network Mobility)

Figure 44 shows the end-to-end delay of the protocols. OLSR has the lowest end-to-end delay at low and high mobility, while AODV outperforms DSR.

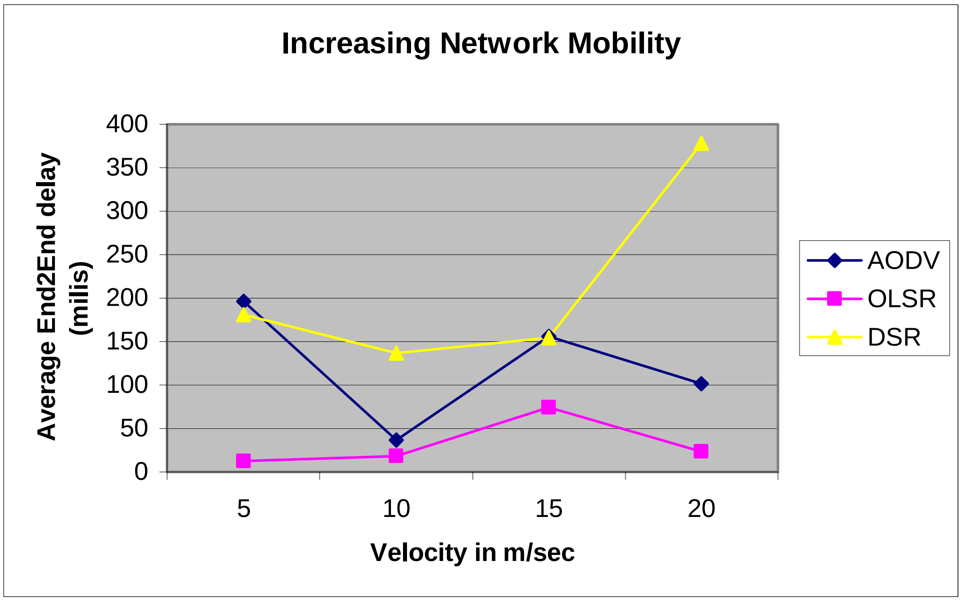
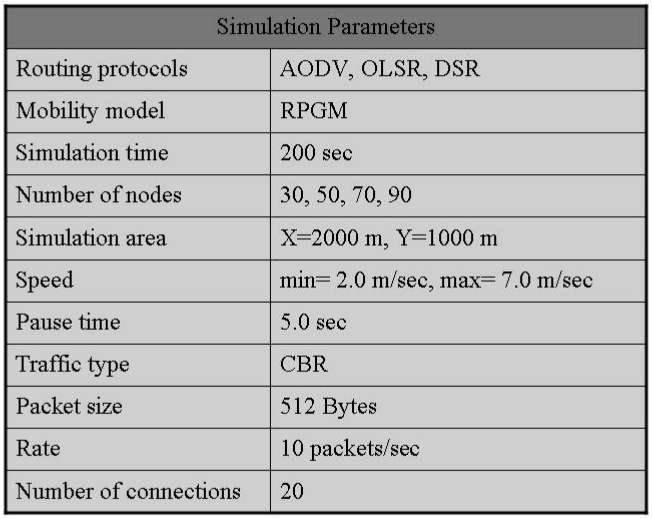


Figure 44. RPGM, End2End Delay (Varying Network Mobility)

That high end-to-end delay in DSR in all cases can be explained by our previous observation for the DSR normalized MAC load, because intermediate nodes need to repair all invalid routes between a source/destination pair in the network, which increases network delay.

5. Varying Node Density

In the final set of the simulation with the RPGM model, we vary the number of nodes in the network. Our objective is to investigate the impact of node density on the protocol’s performance. We use the same simulation area as in our previous simulations and gradually increase the number of nodes in the network. A desirable property of a protocol is to have stable behavior regardless of the number of nodes in the network. However, due to wireless medium limitations, we do not place an inadequate number of nodes in the simulation area. A small number of nodes in a large simulation area will result in low connectivity due to the large distances between nodes. In contrast, a large number of nodes in a small simulation area will result in signal interference, as nodes are located very close to each other. Table 10 shows the simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	RPGM
Simulation time	200 sec
Number of nodes	30, 50, 70, 90
Simulation area	X=2000 m, Y=1000 m
Speed	min= 2.0 m/sec, max= 7.0 m/sec
Pause time	5.0 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	10 packets/sec
Number of connections	20

Table 10. RPGM, Varying Node Density

All protocols have a similar packet delivery ratio, except in the case of 90 nodes, in which OLSR performance drops significantly compared to that of AODV and DSR (Figure 45).

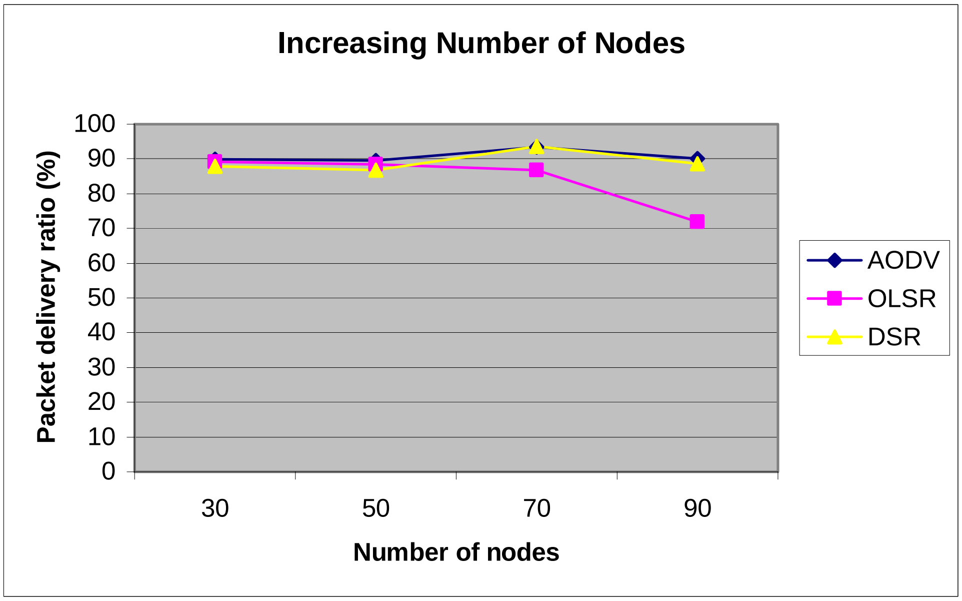


Figure 45. RPGM, Packet Delivery Ratio (Varying Node Density)

Figure 46 shows the normalized routing load. DSR has the lowest normalized routing load, which is almost independent from the number of nodes in the network. AODV has a higher normalized routing load than DSR and OLSR in the case of 30 and 50 nodes. However, AODV scales well when the number of nodes in the network increase. OLSR has a lower normalized routing load than AODV in the case of 30 and 50 nodes that increases exponentially with 90 nodes. This is not a desirable property of a protocol, as that high routing load reveals the OLSR inefficiency to operate properly in a network with an increasing number of nodes. This is a direct result of the OLSR proactive behavior, but we expected that the proposed optimization of the Link State algorithm with the implementation of the MPRs would result in a much lower normalized routing load, thereby increasing OLSR performance.

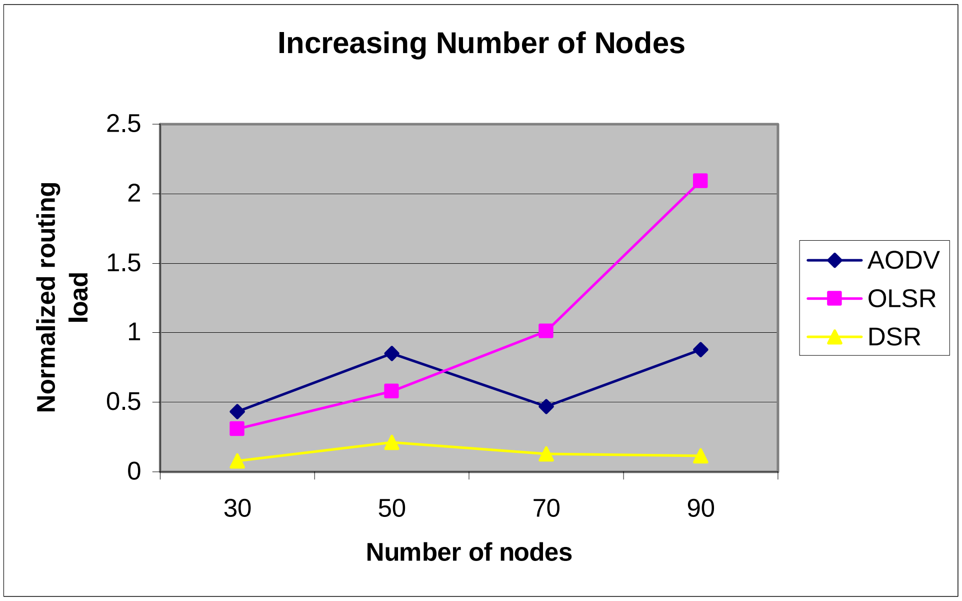


Figure 46. RPGM, Normalized Routing Load (Varying Node Density)

Figure 47 shows the normalized MAC load. OLSR has the lowest normalized MAC load except in the case of 90 nodes, in which OLSR generates a higher number of control packets. That high number of the normalized MAC load reveals that the network is congested, not by data packets, as we keep the data rate constant, but from the routing packets generated by OLSR. The direct result of a congested network is a high end-to-end delay, which increases exponentially in the case of 90 nodes, as we see in Figure 48. Both AODV and DSR present small fluctuations in terms of the end-to-end delay, but generally, their performance is stable in all cases.

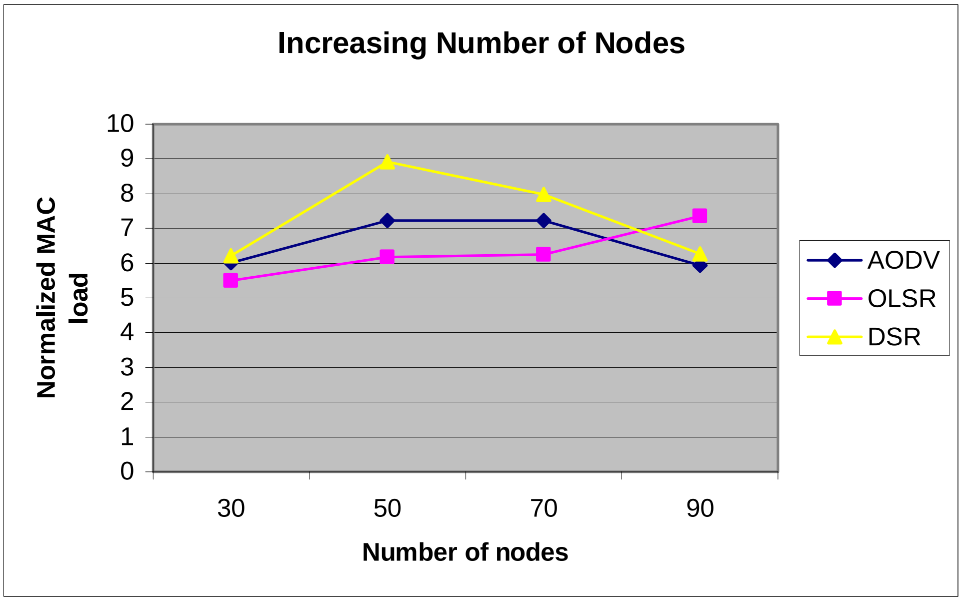


Figure 47. RPGM, Normalized MAC Load (Varying Node Density)

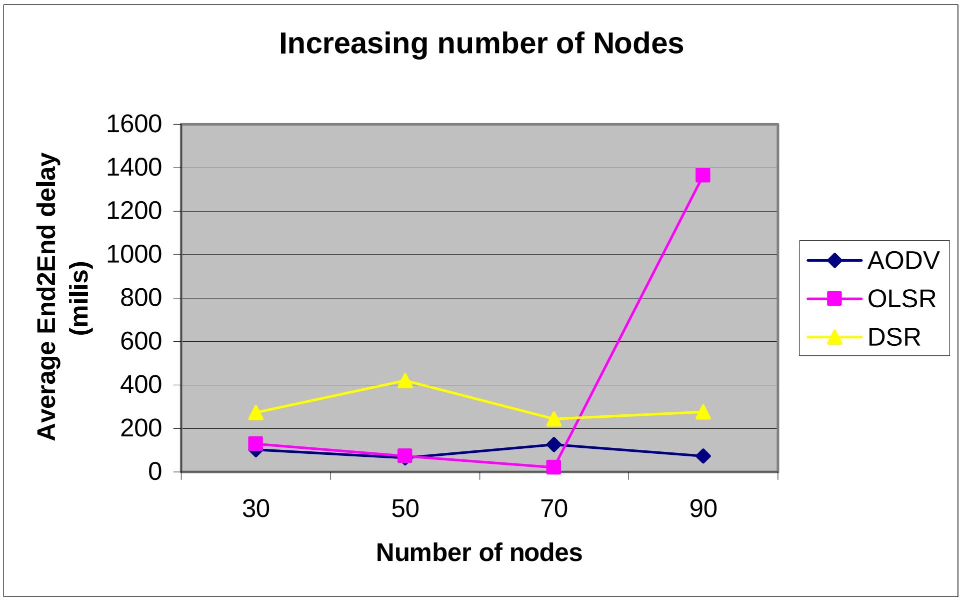
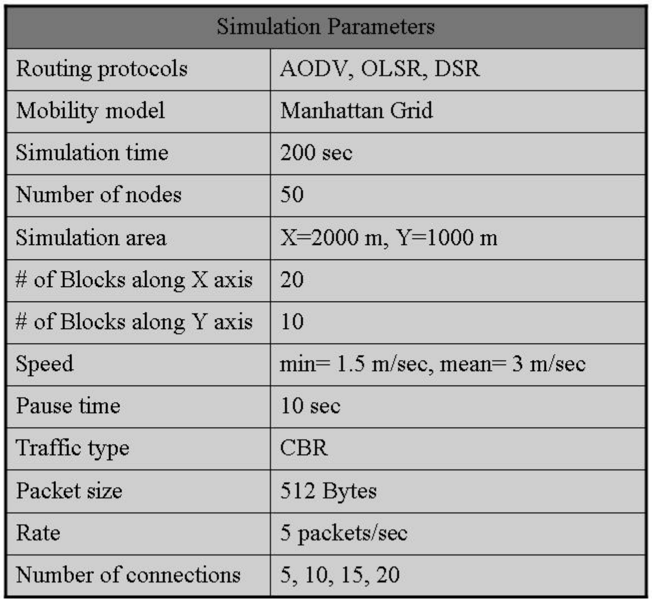


Figure 48. RPGM, End2End Delay (Varying Node Density)

B. MANHATTAN GRID MOBILITY MODEL

1. Varying the Number of Connections

In the first set of simulations, we keep constant the data rate per connection and increase the number of connections in the network. Under the Manhattan Grid mobility model, we use the same size simulation area as in the RPGM model but divide that area into blocks sized 100m by 100m. Thus, we approximate a small neighborhood in an urban area in which mobile nodes operate. However, under that mobility scenario, we reduce the number of connections and the data rate per connection, because the network connectivity is lower than in the RPGM model due to the presence of blocks. While experimenting with a higher number of connections than those we use in the simulation set below, we observed that all protocols presented a very low performance, making any comparison meaningless. Table 11 shows the chosen simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	Manhattan Grid
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
# of Blocks along X axis	20
# of Blocks along Y axis	10
Speed	min= 1.5 m/sec, mean= 3 m/sec
Pause time	10 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	5 packets/sec
Number of connections	5, 10, 15, 20

Table 11. Manhattan Grid, Varying the Number of Connections

Figure 49 shows the packet delivery ratio. The performance of the protocols is much lower than in the RPGM model, even with the lower data rates per connection, and the lower number of connections. The division of the simulation area into blocks seriously affects the protocols’ performance. We observe that, unlike the RPGM model, DSR has the highest packet delivery ratio, while OLSR presents the lowest packet delivery ratio in both mobility models. The packet delivery ratio of AODV in the RPGM model was higher than that of DSR. However, under the Manhattan grid mobility model, the AODV performance is significantly lower than that of DSR.

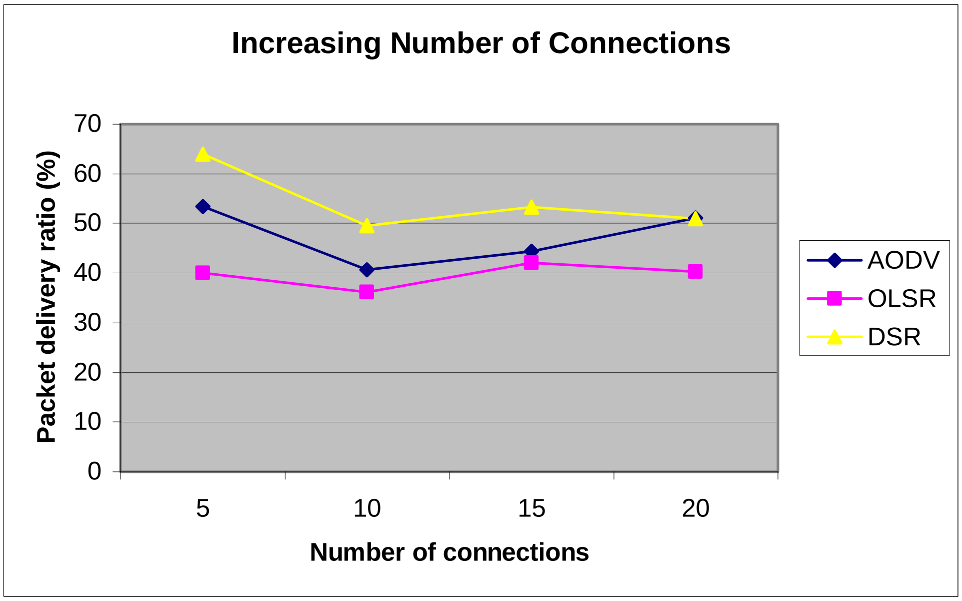


Figure 49. Manhattan Grid, Packet Delivery Ratio (Increasing number of connections)

Figure 50 shows the normalized routing load of the protocols, which is higher than that in the RPGM model by a factor of 10 for all protocols. DSR outperforms both AODV and OLSR, while OLSR has the highest routing load, as expected. By analyzing the simulation trace files, we found that AODV generates a higher number of RREQ and RREP messages than DSR.

Figure 51 shows the normalized MAC load. The OLSR performance is the most stable, due to its proactive behavior, while DSR outperforms AODV, except for the case of 20 connections, unlike the RPGM model. Therefore, we can conclude that DSR can perform better than AODV in networks with low connectivity. The low connectivity in the Manhattan Grid model forces AODV to generate a higher number of routing control messages, which results in a higher normalized MAC load.

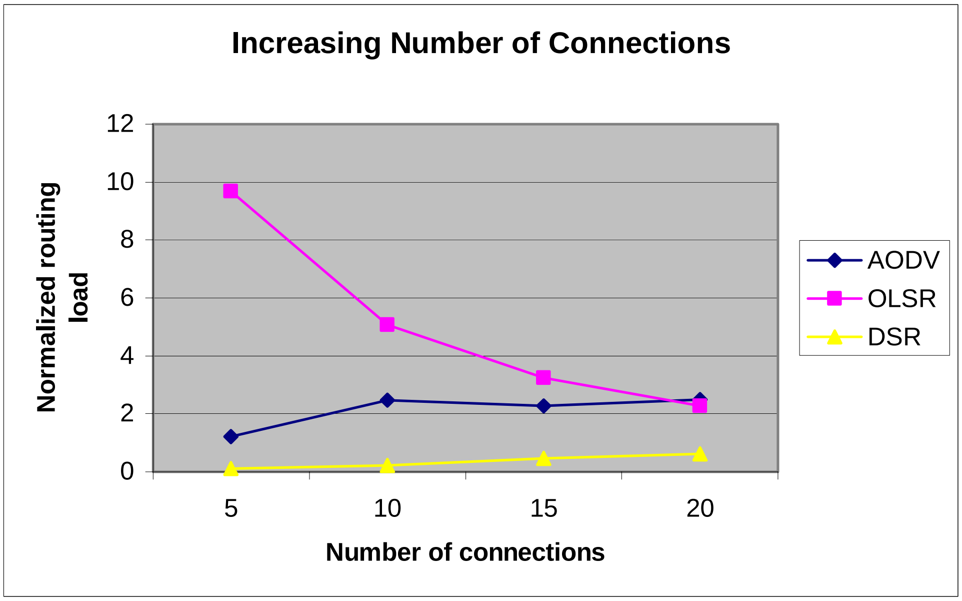


Figure 50. Manhattan Grid, Normalized Routing Load (Increasing number of connections)

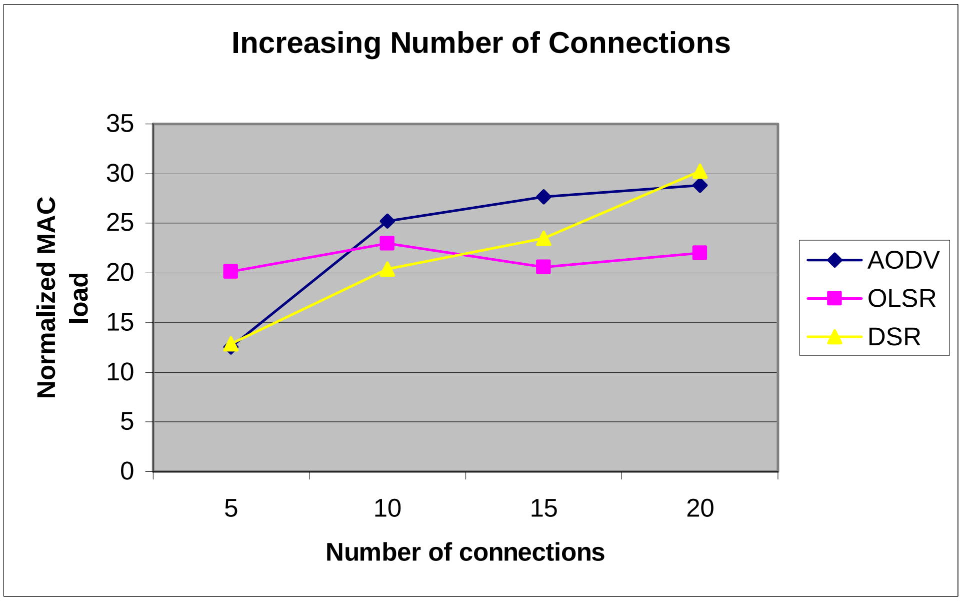


Figure 51. Manhattan Grid, Normalized MAC Load (Increasing number of connections)

Figure 52 shows the end-to-end delay. Unlike the RPGM model, AODV outperforms DSR. The network congestion in the Manhattan Grid model is worse than in our previous simulations with the RPGM model. Both AODV and DSR use a hop-wise path length to determine the best path among the available paths for any source/destination pair. However, the destination node in AODV replies only to the first receiving RREQ sent by the source node. That design ensures, in some way, that the path from the source to the destination node is the shortest in terms of the time required for a data packet to travel over that path. On the other hand, the destination node in DSR replies to all receiving RREQ arriving from different paths. Therefore, the source node in DSR may choose a path that is already congested, causing higher end-to-end delay. OLSR presents the lowest end-to-end delay in both mobility models.

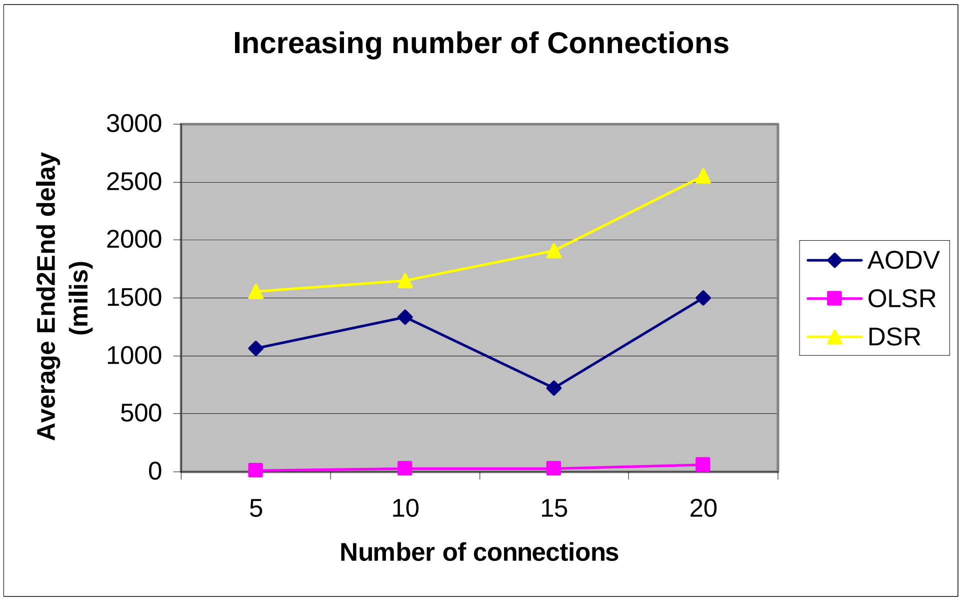
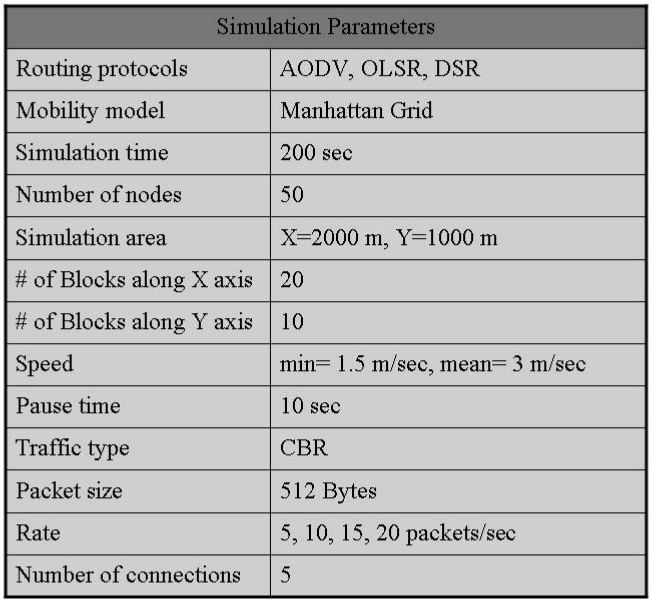


Figure 52. Manhattan Grid, End2End Delay (Increasing number of connections)

2. Varying the Network Load

In the second set of simulations, we keep a constant number of 5 connections and increase the network load from 5 packets/sec (20.480 Kbps) to 20 packets/sec (81.920 Kbps) per connection. Once again, with the Manhattan Grid model we use a lower number of connections than in RPGM to balance network congestion. Table 12 shows the simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	Manhattan Grid
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
# of Blocks along X axis	20
# of Blocks along Y axis	10
Speed	min= 1.5 m/sec, mean= 3 m/sec
Pause time	10 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	5, 10, 15, 20 packets/sec
Number of connections	5

Table 12. Manhattan Grid, Varying the Network load

Figure 53 shows the packet delivery ratio of the protocols. Like the RPGM model, OLSR has the lowest packet delivery ratio, which, however, remains stable in all cases. AODV outperforms DSR except for the case of 5 packets/sec.

DSR presents the lowest routing load (Figure 54), outperforming AODV and OLSR. We have observed the same performance in all of our previous sets of simulations with both mobility models. Although, at this point, we have not finished all of our simulation sets, we can conclude that DSR is a more efficient protocol than AODV and OLSR, in terms of the routing load and wireless medium utilization for data traffic in networks with low mobility and a small number of nodes.

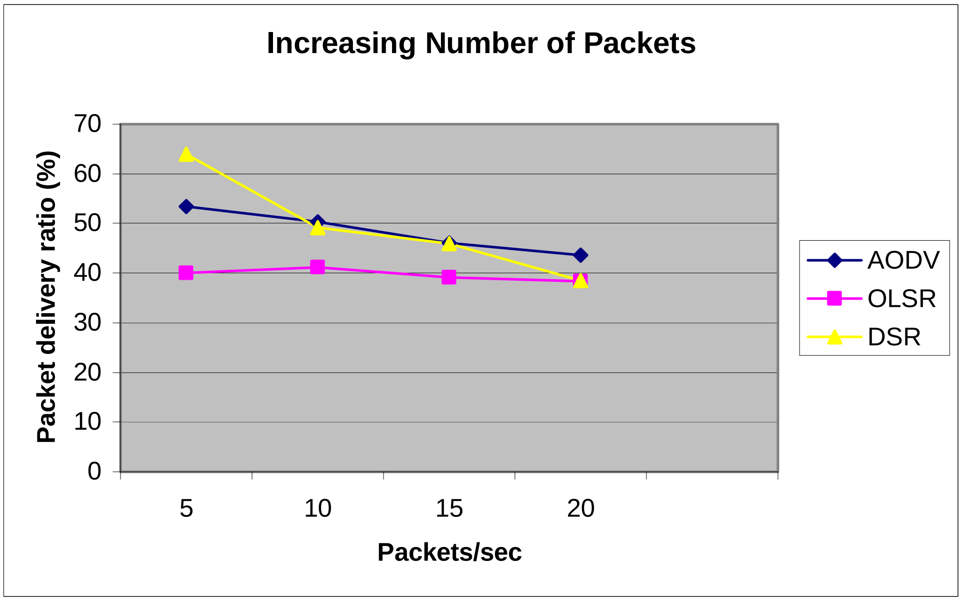


Figure 53. Manhattan Grid, Packet Delivery Ratio (Increasing number of packets)

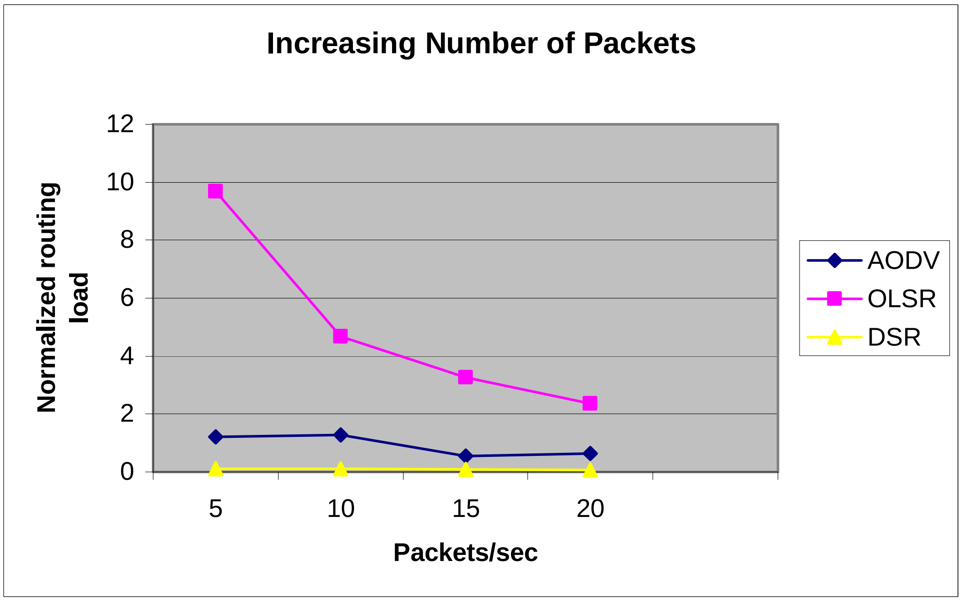


Figure 54. Manhattan Grid, Normalized Routing Load (Increasing number of packets)

Figure 55 shows the normalized MAC load. AODV presents a higher MAC load than OLSR for rates at 10 and 15 packets/sec. DSR presents the lowest MAC load in all cases, which decreases as data rates increase.

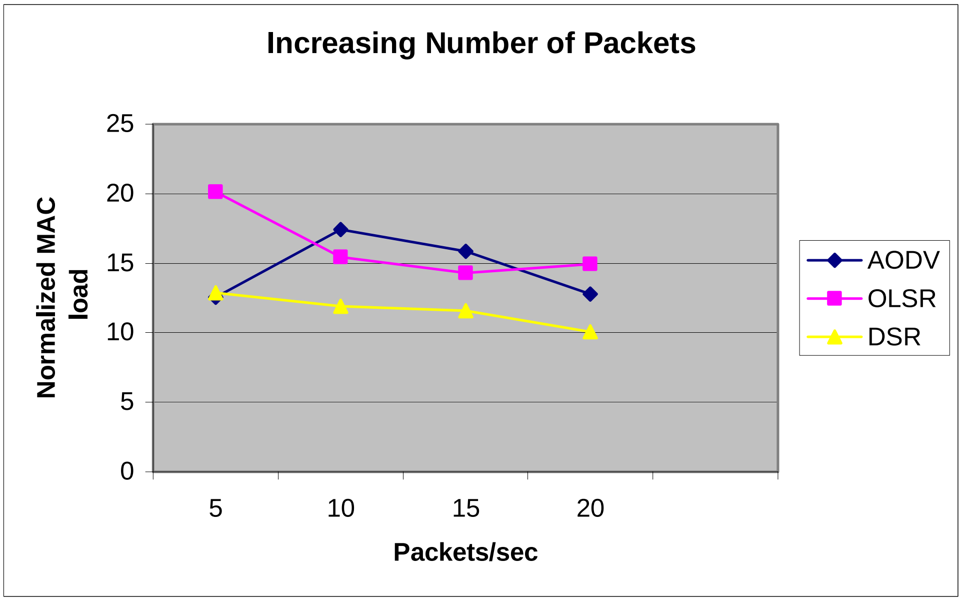


Figure 55. Manhattan Grid, Normalized MAC Load (Increasing number of packets)

Figure 56 shows the end-to-end delay. The superiority of OLSR in terms of end-to-end delay is obvious. Both DSR and AODV have a higher end-to-end delay than OLSR, by a factor that scales from 5 to 100.

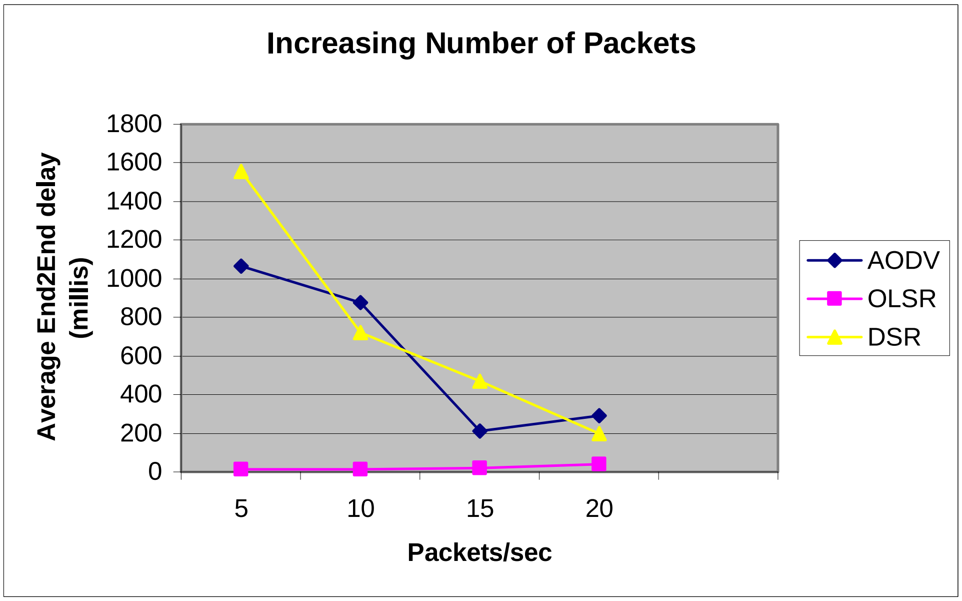
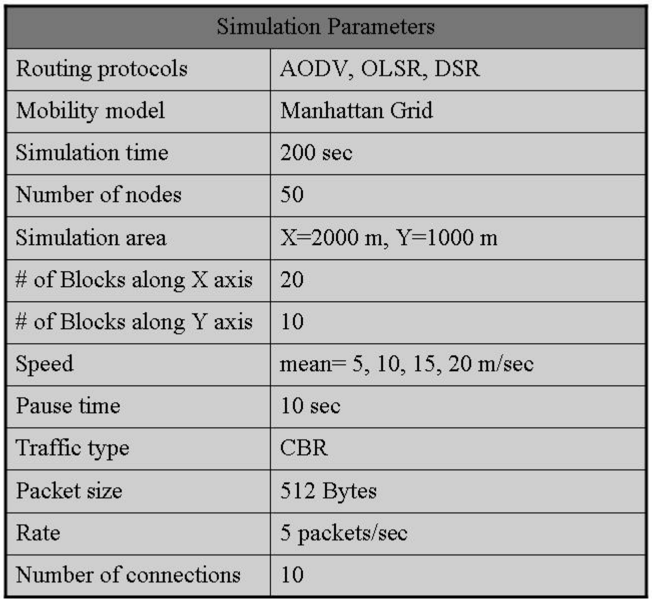


Figure 56. Manhattan Grid, End2End Delay (Increasing number of packets)

By comparing the performance of AODV and DSR, we see that DSR presents a generally higher end-to-end delay than AODV. The reason lies in the way that the destination node in DSR replies to receiving RREQ messages, as we explained in the precious section.

3. Varying Network Mobility

In this set of simulations, we investigate the impact of mobility on the protocol's performance under the Manhattan Grid mobility model. We increase the nodes' velocity from 5 m/sec up to 20 m/sec, with a pause time of 10 sec, and set up 10 connections with a constant data rate of 5 packets/sec per connection. We observed that at higher data rates, with varying mobility, the performance of the protocols was too low for any meaningful comparison. Table 13 shows the simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	Manhattan Grid
Simulation time	200 sec
Number of nodes	50
Simulation area	X=2000 m, Y=1000 m
# of Blocks along X axis	20
# of Blocks along Y axis	10
Speed	mean= 5, 10, 15, 20 m/sec
Pause time	10 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	5 packets/sec
Number of connections	10

Table 13. Manhattan Grid, Varying Network Mobility

Figure 57 shows the packet delivery ratio. We observe that the performance of the protocols follows the same pattern with varying velocity, which is lower at 5 and 15 m/sec and higher at 10 and 20 m/sec. Both AODV and DSR have a similar performance, whereas OLSR has always the lowest performance regardless of the nodes' velocity.

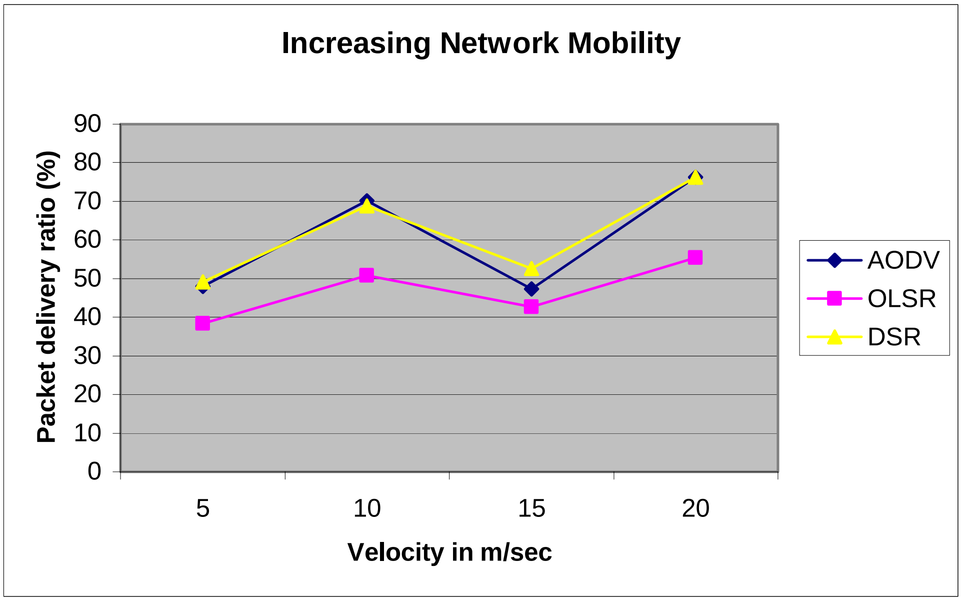


Figure 57. Manhattan Grid, Packet Delivery Ratio (Varying Network Mobility)

Figure 58 shows the normalized routing load. DSR outperforms OLSR and AODV in all cases. Both AODV and DSR present a very stable normalized routing load, while the OLSR normalized routing load is inverse proportional to the packet delivery ratio. This phenomenon can be explained, by the way we calculate the normalized routing load, as the fraction of all routing packets generated by the nodes over the number of all received data packets. As the OLSR routing packets are not highly dependent on the network topology, the fraction of the normalized routing load is inverse proportional to the packet delivery ratio. The higher the packet delivery ratio, the lower the normalized routing load.

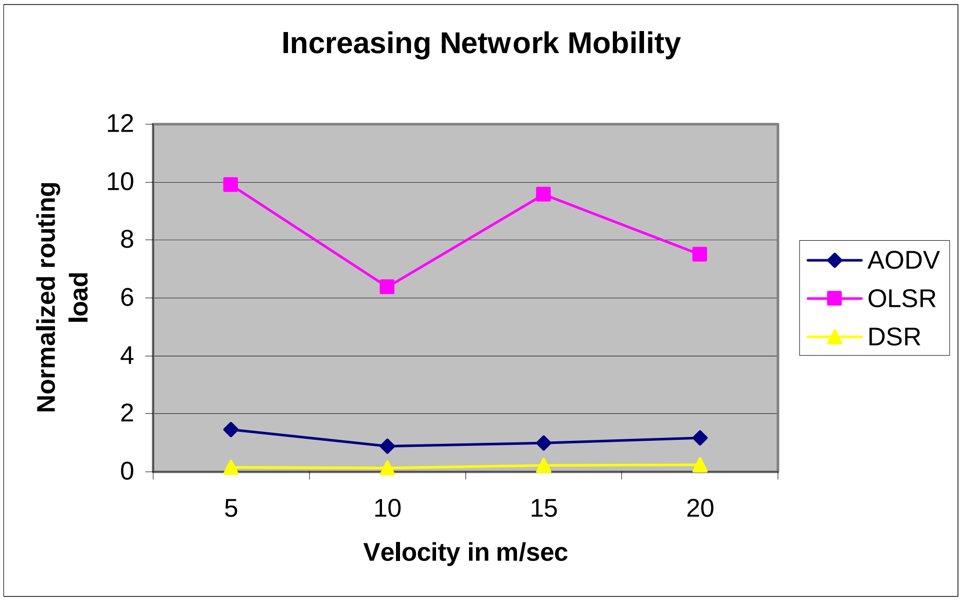


Figure 58. Manhattan Grid, Normalized Routing Load (Varying Network Mobility)

Figure 59 shows the normalized MAC load. Both AODV and DSR have a similar performance, while OLSR presents the highest normalized MAC load in all cases. However, the protocol's performance, in general, is worse by at least a factor of 2 when compared to the RPGM model.

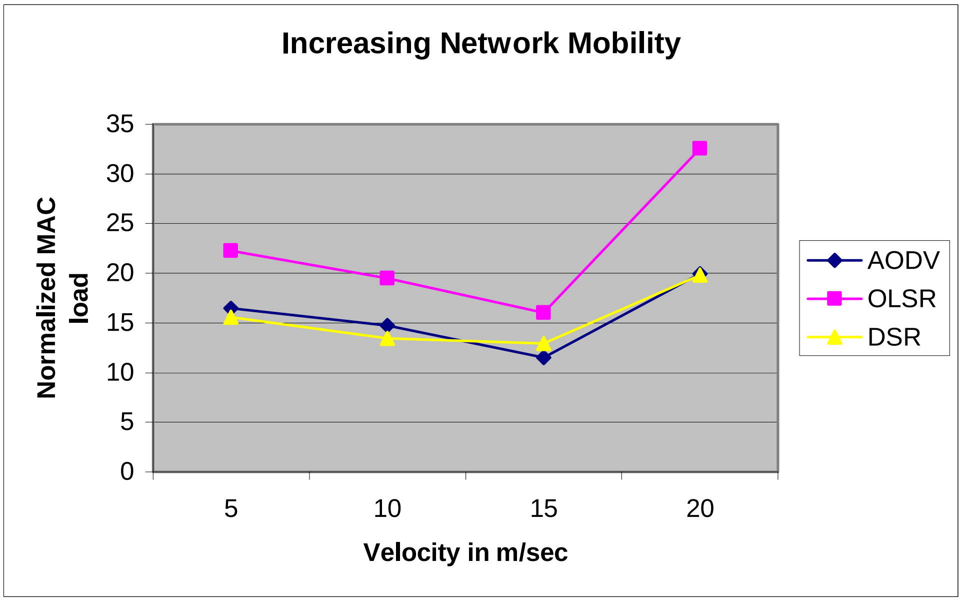


Figure 59. Manhattan Grid, Normalized MAC Load (Varying Network Mobility)

OLSR has the lowest end-to-end delay (Figure 60), which is almost independent of the network mobility. This is a desirable property of a protocol for time-sensitive applications such as video streaming. We have observed the same performance of OLSR with both the RPGM and the Manhattan Grid mobility models. Both AODV and DSR present an unstable performance that is very much dependent on network mobility. For low and high mobility, both protocols have a performance that is very close to that of OLSR. In any other case, both protocols present high end-to-end delay.

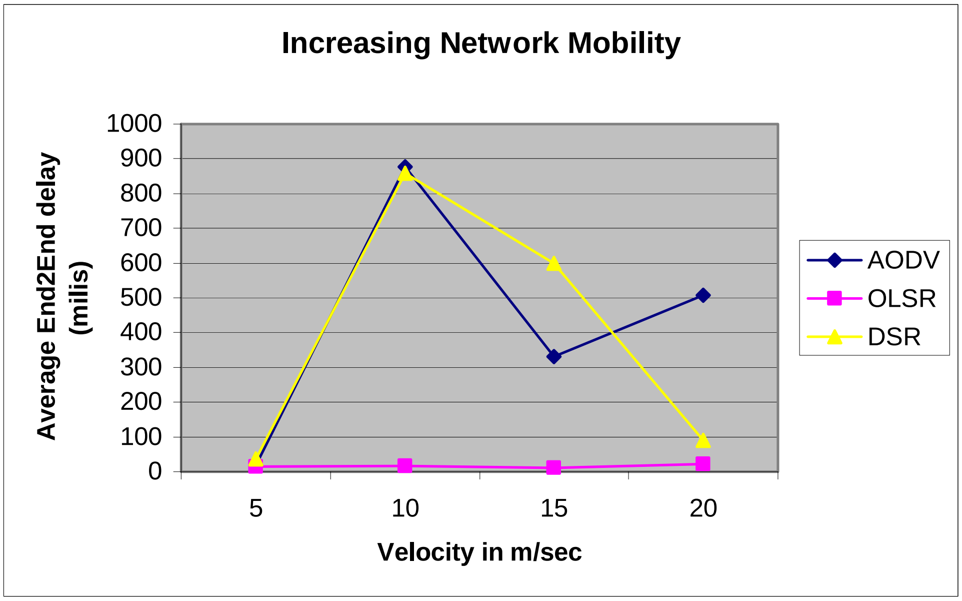
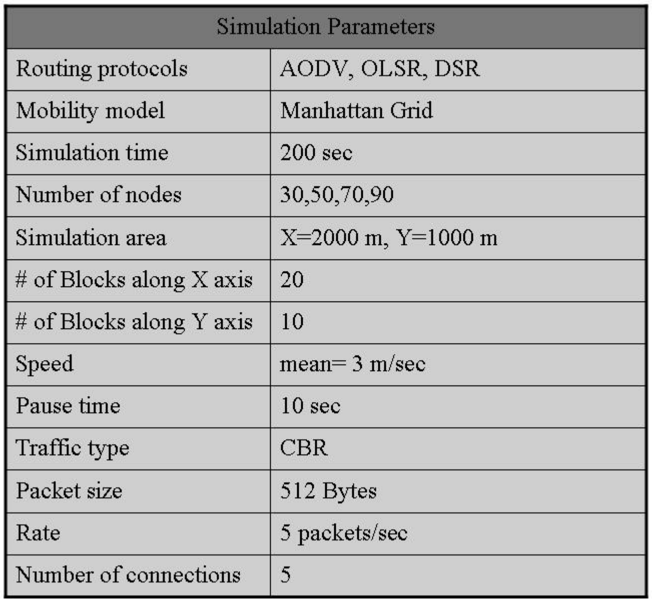


Figure 60. Manhattan Grid, End2End Delay (Varying Network Mobility)

4. Varying Node Density

In the final set of simulations with the Manhattan Grid mobility model, we increase the number of nodes in the same simulation area that we used in all previous simulations with that model. We keep a constant number of 5 connections and a data packet rate of 5 packets/sec while we choose a lower mean velocity of 3 m/sec (10.800 Km/h). Our intention is to investigate the protocol's performance when the number of nodes increases in the simulation area. The desirable behavior of a routing protocol is to present a stable performance when the number of nodes increases in the network. Table 14 shows the simulation parameters.



Simulation Parameters	
Routing protocols	AODV, OLSR, DSR
Mobility model	Manhattan Grid
Simulation time	200 sec
Number of nodes	30,50,70,90
Simulation area	X=2000 m, Y=1000 m
# of Blocks along X axis	20
# of Blocks along Y axis	10
Speed	mean= 3 m/sec
Pause time	10 sec
Traffic type	CBR
Packet size	512 Bytes
Rate	5 packets/sec
Number of connections	5

Table 14. Manhattan Grid, Varying Node Density

Figure 61 shows the packet delivery ratio of the protocols. We observe that all protocols follow the same pattern in all cases and present their best performance in the case of 90 nodes. DSR and AODV have a similar performance, while OLSR presents the worst performance. Once again, the periodic dissemination of HELO and link state packets from OLSR creates a higher congestion in the network that results in a higher number of dropped-data-packets events.

Figure 62 shows the normalized routing load. OLSR has the higher routing load in all cases, while DSR outperforms AODV. DSR is the protocol with the most stable behavior, regardless of the number of nodes in the network. This is a desirable property for a routing protocol, as the routing overhead seems to be independent of the number of nodes in the network.

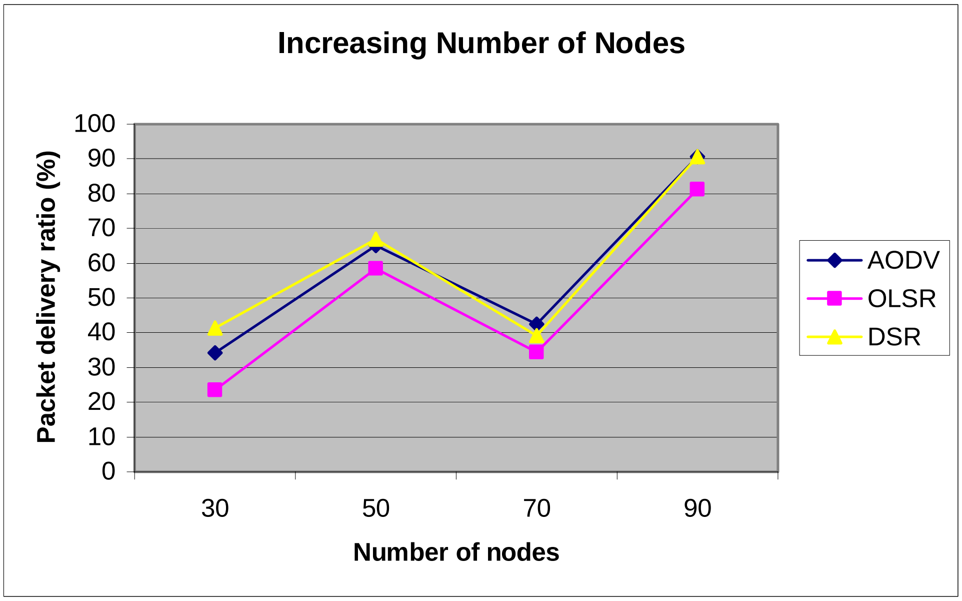


Figure 61. Manhattan Grid, Packet Delivery Ratio (Varying Node Density)

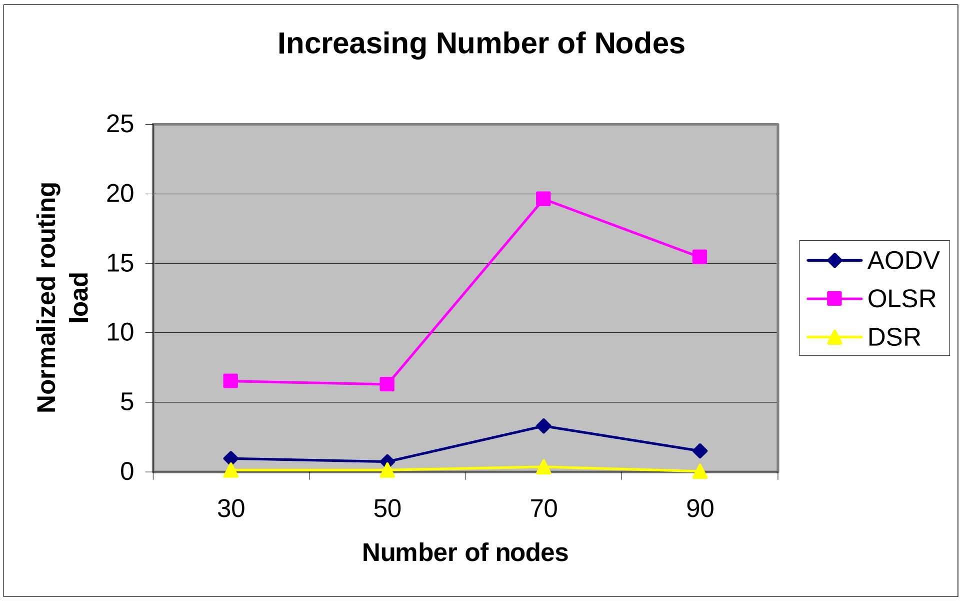


Figure 62. Manhattan Grid, Normalized Routing Load (Varying Node Density)

Figure 63 shows the normalized MAC load. OLSR presents the highest normalized MAC load while DSR and AODV have an almost similar performance. By combining the normalized routing and MAC loads, we can conclude that DSR is a more effective routing protocol than AODV and OLSR in terms of wireless medium utilization for data traffic.

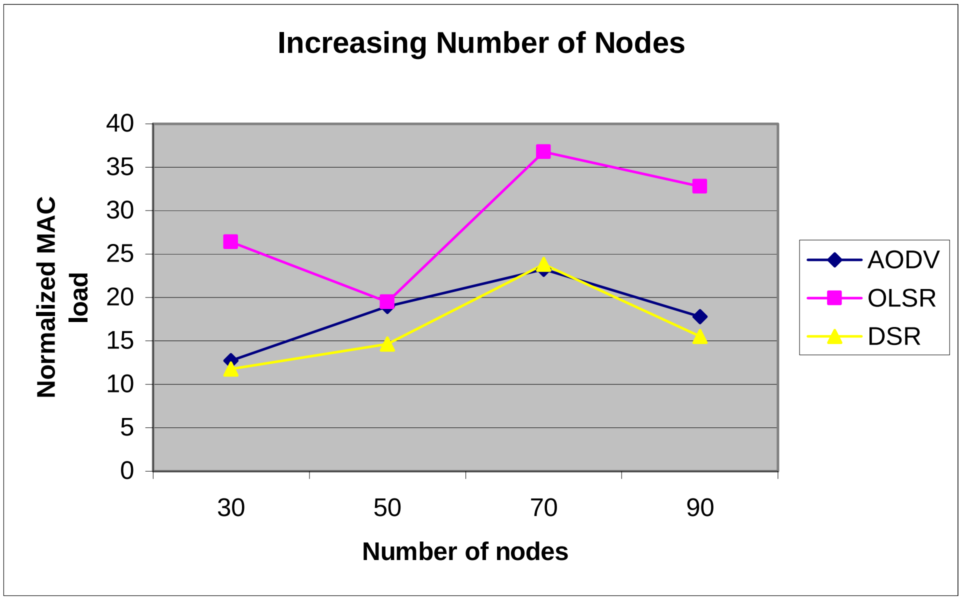


Figure 63. Manhattan Grid, Normalized MAC Load (Varying Node Density)

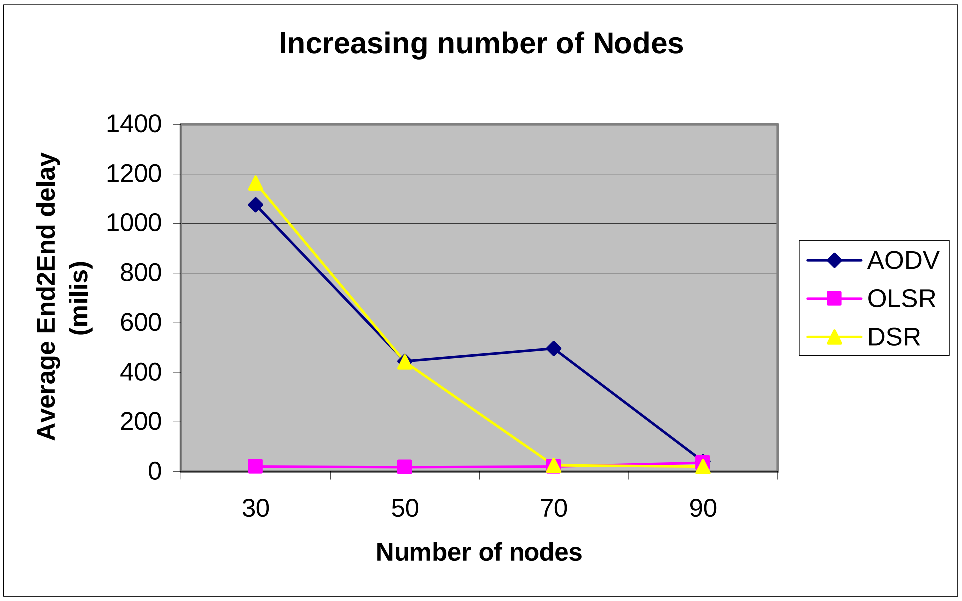


Figure 64. Manhattan Grid, End2End Delay (Varying Node Density)

Finally, we observe in Figure 64 that OLSR has the lowest end-to-end delay, which is independent of the number of nodes in the network. All routing protocols have an identical performance in the case of 90 nodes, because the data packets are more evenly distributed in the network. We observed the same phenomena in our previous simulation with the RPGM model in a network with 70 nodes.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This thesis discusses the evaluation of two reactive routing protocols, AODV and DSR, and one proactive protocol, OLSR, based on simulation results with the network simulator [NS-2]. One hundred and eight simulations under the Reference Point Group Mobility (RPGM) and Manhattan Grid mobility models were conducted, and thirty testing simulations, to choose the simulation parameters in a way that they allowed the routing protocols to present a packet delivery ratio above 50 percent, in order to have meaningful and comparable results. The goals were to better understand the limitations of the tested protocols, to disclose design flaws, and to make recommendations for optimizing their performance. The performance of the tested routing protocols depended strongly on the above two mobility models and the simulation parameters chosen for each simulation set. The thesis conclusions and recommendations for future work are summarized below.

A. CONCLUSIONS

OLSR had the lowest performance in terms of the packet delivery ratio in all of the simulations with both the RPGM and the Manhattan grid mobility model. The reason lies in the proactive behavior of OLSR, because the Multipoint Relay (MPR) nodes flood the network with Topology Control (TC) packets every 5 seconds (default value). Therefore, when the network load increases, data packets are dropped by the mobile nodes due to network congestion caused by the periodic transmission of TC packets.

OLSR presented the lowest end-to-end delay in almost all of the simulations, and in most cases, the end-to-end delay was independent of the varying simulation parameters. OLSR is a good compromise when combining the protocol performance, in terms of the packet delivery ratio and the end-to-end delay. **It is concluded** that, OLSR is the most efficient protocol for time-sensitive applications such as voice and video transmission. However, a few cases were observed in which OLSR had a higher end-to-end delay than the other two reactive protocols (Figures 36 and 40). This is a direct result of the high network congestion in certain areas of the network. By adjusting the TC packet interval and the nodes’ willingness default values to the network attributes (mobility, topology, number of nodes, transport protocol), one could reduce network congestion and end-to-end delay.

AODV performance depended on the mobility models that were used in the simulations. Under the RPGM model with low mobility, AODV has a lower packet delivery ratio (Figures 29 and 33), higher normalized routing (Figures 30 and 34) and MAC loads (Figures 31 and 35), and a higher end-to-end delay (Figures 32 and 36) than DSR. In networks with a small number of nodes and low mobility, AODV does not suggest a good solution as a routing protocol. However, AODV has better performance in networks with higher mobility and a greater number of nodes. Simulation results in those networks suggest that AODV presents a higher packet delivery ratio (Figure 41, Figure 45) and a lower normalized MAC load (Figures 43 and 47) than DSR and OLSR. In addition, AODV performance in terms of end-to-end delay (Figures 44 and 48) is very close to that of OLSR. **It is concluded** that AODV is the proper protocol for any kind of application (voice, video, file transfer, etc.) in networks with high mobility that consist of up to 90 or more nodes.

Under the Manhattan grid mobility model in a network with 50 nodes and low mobility, AODV had a lower packet delivery ratio than DSR but a higher ratio than that of OLSR (Figures 49 and 53). This classification among the three protocols also stands in terms of the normalized routing and MAC loads (Figures 50, 51, 54, and 55). The striking difference among the three protocols is the end-to-end delay, in which the OLSR superiority is obvious (Figures 52 and 56). AODV improves its performance in networks with a greater number of nodes and higher mobility, which, however, remains lower than that of DSR. **It is concluded** that AODV is not the proper protocol in networks with low connectivity, regardless of the network mobility and number of nodes.

With the RPGM reference model and a heavy network load, DSR presented the best performance in terms of packet delivery ratio and end-to-end delay (Figures 33, 36). In most cases, under this mobility model, DSR presented the lowest normalized routing and MAC loads, proving that source routing proves to be an efficient routing mechanism in networks with a small number of nodes and high connectivity, because it utilizes the wireless medium for data traffic in a better way than the other tested protocols.

However, DSR performance decreases in networks with higher mobility (Figures 41, 44), disclosing that source routing cannot efficiently adapt the network topology changes that are caused by the frequent movement of the mobility nodes. The same set of observations was obtained when comparing DSR performance in networks with an increasing number of nodes. Under this scenario, DSR presents lower performance than AODV in terms of the packet delivery ratio and end-to-end delay (Figures 45, 48).

To summarize the above results and observations, **it is concluded** that DSR is a good candidate as the routing protocol in networks with high connectivity, a small number of nodes (up to 100), and low mobility. The high packet delivery ratio and the low end-to-end delay in those networks enable the efficient use of time-sensitive applications, such as voice and video streaming.

DSR presented the higher packet delivery ratio, under the Manhattan mobility model, in a network with 50 nodes and a high number of connections, but its performance in terms of end-to-end delay is poor and lower than that of OLSR and AODV (Figures 49, 52). When the mobility of the network increases, DSR presents almost the same performance as AODV in terms of the packet delivery ratio and end-to-end delay. The same results were observed with a higher number of nodes in the network under the Manhattan mobility model.

It is concluded that DSR is not a good candidate as the routing protocol in networks with low connectivity, regardless of the number of nodes and the network mobility.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Optimized Link State Routing (OLSR)

It is recommended that further experiments be conducted on the value of the TC packet interval to optimize the performance of OLSR when the attributes of the network are known in advance. In a network with low mobility for instance, one should increase the TC time interval, as network topology does not change so frequently and routing tables have valid routes to any source/destination pair for a longer period. Alternatively, in a network with high mobility, one should decrease the TC time interval, as network topology changes more frequently and valid routes expire in short periods. In this way, one could control the number of TC packets in the network, balancing network congestion, and thereby optimizing OLSR performance.

A second optimization of the protocol **is recommended** by adjusting the nodes' willingness value to reflect network topology. In the simulations of this thesis, the value of the nodes' willingness was set to 3, which is the default value in accordance with RFC 3626. That means that a node is willing to act as a MPR for all nodes within a distance of 3 hops away. In a cluster-like network, one can set that value in such a way that a node will not act as an MPR for nodes that lie outside its cluster. Thus, one could reduce the dissemination of OLSR control packets in the network, reducing network congestion and optimizing OLSR performance.

2. Ad Hoc on Demand Distance Vector (AODV)

The main design flaw of AODV is the high number of RREQ and RREP messages, which are generated by the mobile nodes. That high number of messages increases routing overhead in the network, which results in higher network congestion.

An optimization of the AODV protocol **is recommended** by adjusting the time-out value, which is defined as *ACTIVE_ROUTE_TIMEOUT* in RFC 3561, for routes that have previously been used by a node, to reflect a given network topology and mobility. However, to do that, one should know in advance the network mobility and topology, so that one can estimate the optimal time-out value by experimenting with different time-out values. Generally, in networks with low mobility, a large time-out value should be chosen, as network topology does not change so frequently, whereas a small value is more suitable in networks with high mobility.

3. Dynamic Source Routing Protocol (DSR)

The main disadvantage of the protocol is the high end-to-end delay, which is caused by the way the mobile nodes reply to RREQ messages.

A modification of the protocol **is recommended** in the way the mobile nodes reply to incoming RREQ messages. AODV design can be used as an approach to address this particular problem, by forcing the mobile nodes to reply only to the first incoming RREQ message sent by a node in the network. In this way, DSR can discover the least congested path between a source/destination pair and therefore decrease end-to-end delay. An additional benefit of this modification will be a better utilization of the wireless medium, as a lower number of RREP messages will flow the network.

4. Trace Analysis Software

The main objective when creating this software was to provide an easy way to get the desirable quantitative metrics for this thesis. [TraceGraph] is free software for analyzing ns2 trace files and runs on top of [Matlab]. [TraceGraph] provides a sufficient number of network metrics and graphics for analyzing routing protocol performance. However, the [TraceGraph] running time was too high for analyzing large ns-2 trace files and thus acted as a "bottleneck" in the whole simulation process.

The trace analysis software is a simple program written in Java programming language and, in this first version, supports the analysis of old ns-2 trace files for the three routing protocols that were evaluated in this thesis. A further extension of the software can support any other routing protocol for MANETs and can calculate any desirable quantitative metric.

5. General Recommendations for Routing Protocols for MANETS

It is the author's understanding, after studying the routing protocols and running several simulations for this thesis, that there is no protocol that can be applied to all "kinds" of networks. In other words, there is no routing protocol for MANETs that can provide efficient routing to any size of network, commercial or military, with a small or large number of nodes and varying network load and mobility. What is needed to be done is to adjust these protocols to the network attributes. No protocol can be seen as the best solution for all mobility and traffic models. The bottom line: When one knows in advance the mobility of the nodes, the network topology, the degree of connectivity, the type of the transport protocol (UDP or TCP), and the application that is to be used (email, ftp, video, voice, etc.), he can adjust the internal parameters of the protocol (route updates interval, HELLO interval, etc.) to get the best performance of the protocol. Here is where the problem for finding and standardizing just a single protocol, which can solve the routing problem in MANETs, is located. None of the proposed protocols can be THE solution to the routing problem. On the other hand, if one takes any of the proposed routing protocols and adjust its internal parameters to network attributes, he will have a very good protocol, but only for a specific network or similar networks.

A second approach would be a *self-configurable* routing protocol that would be able to adjust its internal parameters to network attributes. This protocol would collect a number of statistics, such as *observed end-to-end delay*, *packet delivery ratio*, *node velocity*, *degree of network connectivity* etc. and would make decisions to adjust its behavior and therefore optimize its performance.

All the work, recommendations and concepts in previous sections in chapter V are left for evaluation and future work.

APPENDIX A SAMPLE TCL SCRIPT

```
#####################################################################
# This is a sample tcl script for use in network simulator 2        #
# Author: Georgios Kioumourtzis                                     #
# Date : Dec 14 2005                                                #
#####################################################################


set val(chan)     Channel/WirelessChannel  ;#Channel Type
set val(prop)     Propagation/TwoRayGround ;# radio-propagation model
set val(netif)    Phy/WirelessPhy          ;# network interface type
set val(mac)      Mac/802_11               ;# MAC type
set val(ifq)      Queue/DropTail/PriQueue  ;# interface queue type
set val(ll)       LL                       ;# link layer type
set val(ant)      Antenna/OmniAntenna      ;# antenna model
set val(ifqlen)   250                      ;# max packet in ifq
set val(nn)       90                       ;# number of mobile nodes
set val(rp)       OLSR                     ;# routing protocol
set val(x)        2020                     ;# X dimension
set val(y)        2020                     ;# Y dimension
set val(cp)       "cbr-50-05-05"           ;# traffic scenario
set val(sc)       "man-90nodes.ns_movements" ;# mobility scenario
set val(seed)     1.0                      ;# random seed
set val(stop)     100.0                    ;# simulation time

#####################################################################
# Control OLSR behavior from this script - commented lines are not
# needed because those are default values
#
#Agent/OLSR set use_mac_    true
#Agent/OLSR set debug_      false
#Agent/OLSR set willingness 3
#Agent/OLSR set hello_ival_ 2
#Agent/OLSR set tc_ival_    5
#####################################################################


######################################################################
# Default settings
######################################################################
LL set mindelay_         50us
LL set delay_            25us
LL set bandwidth_        0;# not used
#Agent/Null set sport_    0
#Agent/Null set dport_    0
Agent/CBR set sport_      0
Agent/CBR set dport_      0
#Agent/TCPSink set sport_ 0
#Agent/TCPSink set dport_ 0
#Agent/TCP set sport_     0
#Agent/TCP set dport_     0
#Agent/TCP set packetsize 512
Mac/802_11 set dataRate_ 2Mb
#Mac/802_11 set RTSThreshold 0
```

```
set AgentTrace           ON
set RouterTrace          ON
set MacTrace             ON
Queue/DropTail/PriQueue  set Prefer_Routing_Protocols 1

######################################################################
# Set values for the antenna position ,Tx and Rx gain
######################################################################
Antenna/OmniAntenna set X_ 0
Antenna/OmniAntenna set Y_ 0
Antenna/OmniAntenna set Z_ 1.5
Antenna/OmniAntenna set Gt_ 1.0
Antenna/OmniAntenna set Gr_ 1.0

######################################################################
# Initialize the sharedMedia interface with parameters to make it
# work like the 914MHz Lucent WaveLAN DSSS radio
######################################################################
Phy/WirelessPhy set CPThresh_ 10.0
Phy/WirelessPhy set CSThresh_ 1.559e-11
Phy/WirelessPhy set RXThresh_ 3.652e-10
Phy/WirelessPhy set Rb_ 2*1e6
Phy/WirelessPhy set Pt_ 0.2818
Phy/WirelessPhy set freq_ 914e+6
Phy/WirelessPhy set L_ 1.0
Phy/WirelessPhy set dataRate_ 2Mb

puts "simulation time "
puts $val(stop)

######################################################################
# Initialize Global Variables
######################################################################

set ns_           [new Simulator]
#$ns_ use-scheduler Heap
$ns_ use-scheduler List
#$ns_ use-scheduler RealTime
set tracefd     [open olsr-50-05-05-90nodes.tr w]
#$ns_ use-newtrace
$ns_ trace-all $tracefd

#set namtrace [open olsr-50-10-10-200sec.nam w]
#$ns_ namtrace-all-wireless $namtrace $val(x) $val(y)

######################################################################
# set up topography object
######################################################################
set topo       [new Topography]
$topo load_flatgrid $val(x) $val(y)

######################################################################
# Create God
######################################################################
create-god $val(nn)
```

```
######################################################################
# Create channel #1
######################################################################
set chan_1_ [new $val(chan)]
#set chan_2_ [new $val(chan)]

######################################################################
# Create nodes
######################################################################
$ns_ node-config -adhocRouting $val(rp) \
            -llType $val(ll) \
            -macType $val(mac) \
            -ifqType $val(ifq) \
            -ifqLen $val(ifqlen) \
            -antType $val(ant) \
            -propType $val(prop) \
            -phyType $val(netif) \
            -topoInstance $topo \
            -agentTrace ON \
            -routerTrace ON \
            -macTrace ON \
            -movementTrace ON \
            -channel $chan_1_

for {set i 0} {$i < $val(nn)} {incr i} {
    set node_($i) [$ns_ node]
   # set r_($i) [$node_($i) set ragent_]
    # $ns_ at 0.0 "$r_($i) radius 2.0"
    $node_($i) random-motion 0
}

######################################################################
# Define node movement model
######################################################################
puts "Loading connection pattern..."
source $val(cp)

######################################################################
# Define traffic model
######################################################################
puts "Loading scenario file..."
source $val(sc)

######################################################################
# Define node initial position in nam
######################################################################

for {set i 0} {$i < $val(nn)} {incr i} {
      $ns_ initial_node_pos $node_($i) 50

}

######################################################################
# Tell nodes when the simulation ends
######################################################################
for {set i 0} {$i < $val(nn)} {incr i} {
    $ns_ at $val(stop).0 "$node_($i) reset";
}

$ns_ at  $val(stop).002 "puts \"NS EXITING...\"; $ns_ halt"

puts $tracefd "M 0.0 nn $val(nn) x $val(x) y $val(y) rp $val(rp)"
puts $tracefd "M 0.0 sc $val(sc) cp $val(cp) seed $val(seed)"
puts $tracefd "M 0.0 prop $val(prop) ant $val(ant)"


puts "Starting Simulation..."
$ns_ run
```

APPENDIX B SAMPLE NS-2 TRACE FILE

```
######################################################################
# This is a trace file generated by ns-2 during the simulation      #
######################################################################
M 0.0 nn 30 x 2020 y 2020 rp OLSR
M 0.0 sc man-30nodes.ns_movements cp cbr-50-05-05 seed 1.0
M 0.0 prop Propagation/TwoRayGround ant Antenna/OmniAntenna
M 0.00000 3 (1002.18, 210.00, 0.00), (998.56, 210.00), 2.96
M 0.00000 4 (1056.64, 310.00, 0.00), (1040.54, 310.00), 2.84
M 0.00000 5 (410.00, 258.41, 0.00), (410.00, 260.07), 2.87
M 0.00000 8 (910.00, 531.22, 0.00), (910.00, 532.33), 3.15
M 0.00000 11 (1118.74, 910.00, 0.00), (1110.00, 910.00), 2.77
M 0.00000 12 (67.42, 610.00, 0.00), (69.44, 610.00), 3.07
M 0.00000 13 (310.00, 41.17, 0.00), (310.00, 36.12), 3.25
M 0.00000 14 (1873.15, 1010.00, 0.00), (1878.45, 1010.00), 2.90
M 0.00000 16 (1010.00, 564.50, 0.00), (1010.00, 562.09), 2.90
M 0.00000 19 (210.00, 229.33, 0.00), (210.00, 232.34), 2.95
M 0.00000 20 (487.54, 210.00, 0.00), (487.26, 210.00), 2.82
M 0.00000 21 (178.76, 110.00, 0.00), (174.87, 110.00), 3.00
M 0.00000 25 (1385.89, 210.00, 0.00), (1388.85, 210.00), 3.14
s 0.000169789 _0_ RTR  --- 0 OLSR 48 [0 0 0 0] ------- [0:255 -1:255 32
0] [1 0 [HELLO 0 0 0]]
s 0.000824789 _0_ MAC  --- 0 OLSR 100 [0 ffffffff 0 800] ------- [0:255
-1:255 32 0] [1 0 [HELLO 0 0 0]]
r 0.001625368 _25_ MAC  --- 0 OLSR 48 [0 ffffffff 0 800] ------- [0:255
-1:255 32 0] [1 0 [HELLO 0 0 0]]
r 0.001625589 _2_ MAC  --- 0 OLSR 48 [0 ffffffff 0 800] ------- [0:255
-1:255 32 0] [1 0 [HELLO 0 0 0]]
r 0.001650368 _25_ RTR  --- 0 OLSR 48 [0 ffffffff 0 800] ------- [0:255
-1:255 32 0] [1 0 [HELLO 0 0 0]]
r 0.001650589 _2_ RTR  --- 0 OLSR 48 [0 ffffffff 0 800] ------- [0:255
-1:255 32 0] [1 0 [HELLO 0 0 0]]
s 0.044061336 _1_ RTR  --- 1 OLSR 48 [0 0 0 0] ------- [1:255 -1:255 32
0] [1 0 [HELLO 1 0 0]]
s 0.044316336 _1_ MAC  --- 1 OLSR 100 [0 ffffffff 1 800] ------- [1:255
-1:255 32 0] [1 0 [HELLO 1 0 0]]
r 0.045116854 _21_ MAC  --- 1 OLSR 48 [0 ffffffff 1 800] ------- [1:255
-1:255 32 0] [1 0 [HELLO 1 0 0]]
r 0.045141854 _21_ RTR  --- 1 OLSR 48 [0 ffffffff 1 800] ------- [1:255
-1:255 32 0] [1 0 [HELLO 1 0 0]]
s 0.045678458 _22_ RTR  --- 2 OLSR 48 [0 0 0 0] ------- [22:255 -1:255
32 0] [1 0 [HELLO 22 0 0]]
s 0.046193458 _22_ MAC  --- 2 OLSR 100 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.046993798 _27_ MAC  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.046993922 _6_ MAC  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.046993930 _7_ MAC  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.046994099 _26_ MAC  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
```

```
r 0.046994246 _20_ MAC  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.047018798 _27_ RTR  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.047018922 _6_ RTR  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.047018930 _7_ RTR  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.047019099 _26_ RTR  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
r 0.047019246 _20_ RTR  --- 2 OLSR 48 [0 ffffffff 16 800] -------
[22:255 -1:255 32 0] [1 0 [HELLO 22 0 0]]
s 0.054599236 _12_ RTR  --- 3 OLSR 48 [0 0 0 0] ------- [12:255 -1:255
32 0] [1 0 [HELLO 12 0 0]]
s 0.054794236 _12_ MAC  --- 3 OLSR 100 [0 ffffffff c 800] -------
[12:255 -1:255 32 0] [1 0 [HELLO 12 0 0]]
s 0.056015658 _14_ RTR  --- 4 OLSR 48 [0 0 0 0] ------- [14:255 -1:255
32 0] [1 0 [HELLO 14 0 0]]
s 0.056310658 _14_ MAC  --- 4 OLSR 100 [0 ffffffff e 800] -------
[14:255 -1:255 32 0] [1 0 [HELLO 14 0 0]]
s 0.056904124 _5_ RTR  --- 5 OLSR 48 [0 0 0 0] ------- [5:255 -1:255 32
0] [1 0 [HELLO 5 0 0]]
s 0.056979124 _5_ MAC  --- 5 OLSR 100 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057110785 _10_ MAC  --- 4 OLSR 48 [0 ffffffff e 800] -------
[14:255 -1:255 32 0] [1 0 [HELLO 14 0 0]]
r 0.057135785 _10_ RTR  --- 4 OLSR 48 [0 ffffffff e 800] -------
[14:255 -1:255 32 0] [1 0 [HELLO 14 0 0]]
r 0.057779429 _20_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057779508 _6_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057779683 _27_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057779798 _19_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057779803 _26_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057779922 _13_ MAC  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804429 _20_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804508 _6_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804683 _27_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804798 _19_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804803 _26_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
r 0.057804922 _13_ RTR  --- 5 OLSR 48 [0 ffffffff 5 800] ------- [5:255
-1:255 32 0] [1 0 [HELLO 5 0 0]]
s 0.082072703 _4_ RTR  --- 6 OLSR 48 [0 0 0 0] ------- [4:255 -1:255 32
0] [1 0 [HELLO 4 0 0]]
```

APPENDIX C SAMPLE TRAFFIC SCENARIO FILE

```
#####################################################################
# This is a traffic scenario file generated by ns-2                 #
#####################################################################
#
# nodes: 50, max conn: 5, send rate: 0.20000000000000001, seed: 1.0
#
#
# 1 connecting to 2 at time 2.5568388786897245
#
set udp_(0) [new Agent/UDP]
$ns_ attach-agent $node_(1) $udp_(0)
set null_(0) [new Agent/Null]
$ns_ attach-agent $node_(2) $null_(0)
set cbr_(0) [new Application/Traffic/CBR]
$cbr_(0) set packetSize_ 512
$cbr_(0) set interval_ 0.20000000000000001
$cbr_(0) set random_ 1
$cbr_(0) set maxpkts_ 10000
$cbr_(0) attach-agent $udp_(0)
$ns_ connect $udp_(0) $null_(0)
$ns_ at 2.5568388786897245 "$cbr_(0) start"
#
# 4 connecting to 5 at time 56.333118917575632
#
set udp_(1) [new Agent/UDP]
$ns_ attach-agent $node_(4) $udp_(1)
set null_(1) [new Agent/Null]
$ns_ attach-agent $node_(5) $null_(1)
set cbr_(1) [new Application/Traffic/CBR]
$cbr_(1) set packetSize_ 512
$cbr_(1) set interval_ 0.20000000000000001
$cbr_(1) set random_ 1
$cbr_(1) set maxpkts_ 10000
$cbr_(1) attach-agent $udp_(1)
$ns_ connect $udp_(1) $null_(1)
$ns_ at 56.333118917575632 "$cbr_(1) start"
#
# 4 connecting to 6 at time 146.96568928983328
#
set udp_(2) [new Agent/UDP]
$ns_ attach-agent $node_(4) $udp_(2)
set null_(2) [new Agent/Null]
$ns_ attach-agent $node_(6) $null_(2)
set cbr_(2) [new Application/Traffic/CBR]
$cbr_(2) set packetSize_ 512
$cbr_(2) set interval_ 0.20000000000000001
$cbr_(2) set random_ 1
$cbr_(2) set maxpkts_ 10000
$cbr_(2) attach-agent $udp_(2)
$ns_ connect $udp_(2) $null_(2)
$ns_ at 146.96568928983328 "$cbr_(2) start"
#
```

```
# 6 connecting to 7 at time 55.634230382570173
#
set udp_(3) [new Agent/UDP]
$ns_ attach-agent $node_(6) $udp_(3)
set null_(3) [new Agent/Null]
$ns_ attach-agent $node_(7) $null_(3)
set cbr_(3) [new Application/Traffic/CBR]
$cbr_(3) set packetSize_ 512
$cbr_(3) set interval_ 0.20000000000000001
$cbr_(3) set random_ 1
$cbr_(3) set maxpkts_ 10000
$cbr_(3) attach-agent $udp_(3)
$ns_ connect $udp_(3) $null_(3)
$ns_ at 55.634230382570173 "$cbr_(3) start"
#
# 7 connecting to 8 at time 29.546173154165118
#
set udp_(4) [new Agent/UDP]
$ns_ attach-agent $node_(7) $udp_(4)
set null_(4) [new Agent/Null]
$ns_ attach-agent $node_(8) $null_(4)
set cbr_(4) [new Application/Traffic/CBR]
$cbr_(4) set packetSize_ 512
$cbr_(4) set interval_ 0.20000000000000001
$cbr_(4) set random_ 1
$cbr_(4) set maxpkts_ 10000
$cbr_(4) attach-agent $udp_(4)
$ns_ connect $udp_(4) $null_(4)
$ns_ at 29.546173154165118 "$cbr_(4) start"
#
#Total sources/connections: 4/5
#
```

APPENDIX D SIMULATION ANALYSIS PROGRAM SOURCE CODE

A. MAIN CLASS OF THE PROGRAM

```
/**
 * <p>Title: Trace File Analyzer</p>
 *<p>Description: This is a simple java program to analyze ns2
 * trace files. </p>
 *<p>Copyright: Copyright (c) 2005</p>
 * @author Georgios Kioumourtzis
 * @version 1.0
 */

/**
 * The main class of the program.
 */

class TraceAnalyzerMain {

    /** The object of ProcessData class */
    private static ProcessData processData;

    /** The main method of the program. It calls the top level
    method start()
    */

    public static void main(String[] args) {
        start();
    }

     /**
     * The top level method of the program. It calls all other
     * methods
     */

     private static void start() {
        processData = new ProcessData();
        processData.process();
        processData.printSimulationStats();
    }
}
```

B. CLASS TRACE FILE

```
import java.io.*;
import javax.swing.JFileChooser;

/**
* This class opens the ns2 trace file, reads the file line by
* line and saves the simulation results in an output file
```

```
      */



      class TraceFile {

      //---------------------------------------------------------------
      //                          Data Members
      //---------------------------------------------------------------
          /** The constant for empty string */
             private static final String EMPTY_STRING = "";

          /** The generic filepath separator */
            private static String fileSeparator =
            System.getProperty("file.separator");

          /** The generic line terminator */
            private static String lineTerminator =
            System.getProperty("line.separator");

          /** The object for buffered reader */
            private BufferedReader bufReader;

      //---------------------------------------------------------------
      //                           Constructor
      //---------------------------------------------------------------
          /**
           * Default constructor
           */
          public TraceFile() {
              bufReader = null;
          }

          /**
           * Opens a file for input.
           * @throw IOException
           */

          public void open() throws IOException {
              JFileChooser chooser = new
JFileChooser(System.getProperty("user.dir"));
              int reply = chooser.showOpenDialog(null);
              if (reply == JFileChooser.APPROVE_OPTION) {
                  open(chooser.getSelectedFile().getAbsolutePath());
              }
          }


          /**
           * Opens the designated textfile.
           * @param filename name of the textfile to open
           * @throw IOException
           */

          public void open(String filename) throws IOException {
              File inFile = new File(filename);
              FileReader fileReader = new FileReader(inFile);
              bufReader = new BufferedReader(fileReader);
          }


          /**
           * Returns the next line of input as a string. If
           * the end of file is reached, an empty string
           * is returned.
           * @return the next line of input string
           * @throw IOException when the file is not open
           */

          public String readNext() throws IOException {
              if (bufReader == null) {
                  throw new IOException("File is not opened yet");
              }
              String line = bufReader.readLine();
              if (line == null) {
                  line = "";
              }
              return line;
          }

          /**
           * Save the data to a text file. The file to save
           * the data is selected via a file chooser dialog.
           * @param data text data to be saved
           * @exception IOException
           */

          public void save(String data) throws IOException {
              JFileChooser chooser = new
JFileChooser(System.getProperty("user.dir"));
              int reply = chooser.showSaveDialog(null);
              if (reply == JFileChooser.APPROVE_OPTION) {
                  save(chooser.getSelectedFile().getAbsolutePath(),
data);
              }
          }

          /**
           * Saves the data to the designated textfile.
           * @param data to be saved
           * @param filename the file to be saved
           * @exception IOException
           */

          public void save(String filename, String data) throws
IOException {
              File outFile = new File(filename);
              FileOutputStream outFileStream = new
FileOutputStream(outFile);
              PrintWriter outStream = new PrintWriter(outFileStream);
              outStream.print(data);
              outStream.close();
          }
```

```
}
```

C. CLASS FILE ANALYZER

```
import java.awt.List;
import java.io.IOException;
import java.util.StringTokenizer;
import java.util.regex.Matcher;
import java.util.regex.Pattern;


/** This class analyzes the results of the ns2 trace file. It
 * uses mainly the Pattern and Matcher classes and creates two
 * Lists (Received packet list and Send Packet List). From these
 * two lists we further process the data of the ns2 trace file
 */

public class FileAnalyzer {

//-----------------------------------------------------------------
//                          Data Members
//-----------------------------------------------------------------
    /** The object of the Pattern class */
    Pattern pat;

    /** The object of the Matcher class */
    Matcher mat;

    /** The Default agent type */
    private static final String DEFAULT_AGENT = "NONE";

    /** The String to hold the agent type*/
    String agent;

    /** The object to open and read the ns2 trace file */
    TraceFile trFile;

    /** The number of sent data packets */
    private int sentPkts;

    /** The number of received data packets */
    private int rcvPkts;

    /** The object to create a List of the sent data packets.
    * We keep two important values. The data packet sequence
    * number and the time that the packet was sent by the Agent
    (AGT) */
    List sentPktList;

    /** The object to create a List of the received data packets.
    *  We keep two important values. The data packet sequence
    * number and the time that the packet received by the Agent
    * (AGT)*/
    List rcvPktList;

    /** The routing packets (REQUEST, REPLY, ERROR) generated
     * by the AODV routing protocol
     */
    private int generatedAODVPkts;

    /** The routing packets generated
     * by the DSR routing protocol
     */
    private int generatedDSRkts;

    /** The routing packets (HELO,TC) generated
     * by the OLSR routing protocol
     */

    private int generatedOLSRPkts;
    /** The MAC layer packets generated by the nodes.
     * They include ARP,CTS,RTS, and ACK packets.
     */

    private int generatedMACPkts;
    /** The number of total drop data packts and the MAC and
     *  the Network Layers
     */

    private int droppedPkts;
    /** The number of forwarded data packets by the Routing
    Agent
    */
    private int frwPkts;

    StringBuilder strBuilder;
    private double bytesSent;
    private double bytesReceived = 0.0;

//-----------------------------------------------------------
//                           Constructor
//---------------------------------------------------------------
    /**
     * The constructor of the class
     */
    public FileAnalyzer() {
        trFile = new TraceFile();
        sentPktList = new List();
        rcvPktList = new List();
        strBuilder = new StringBuilder();
        generatedAODVPkts = 0;
        generatedDSRkts = 0;
        generatedOLSRPkts = 0;
        generatedMACPkts = 0;
        droppedPkts = 0;
        frwPkts = 0;
        try {
            jbInit();
        } catch (Exception ex) {
            ex.printStackTrace();
        }
    }

//---------------------------------------------------------------
//                           Public Methods
//---------------------------------------------------------------

    /** This method starts the functions of the class
     *  FileAnalyzer
     */

    public void analyze() {
        readData();
    }

    /**
     * The Getter method  for the total number of received
     * data packets by all nodes
     * @return the total number of received data packets by
     * all nodes
     */

    public int getRcvPkts() {
        return this.rcvPkts;
    }

    /**
     * The Getter method  for the total number of sent
     * data packets by all nodes
     * @return the total number of sent data packets by all nodes
     */
    public int getSentPkts() {
        return this.sentPkts;
    }

    /**
     * The Getter method  for the total number of AODV routing
     * packets
     * @return the total number of AODV data packets generated
     * by all nodes
     */
    public int getGeneratedAODVPkts() {
        return generatedAODVPkts;
    }

    /**
     * The Getter method  for the total number of ZRP routing
     * packets
     * @return the total number of AODV data packets generated
     * by all nodes
     */
    public int getGeneratedDSRkts() {
        return generatedDSRkts;
    }
```

```
/**
 * The Getter method for the total number of OLSR
 * routing packets
 * @return the total number of AODV data packets generated
 * by all nodes
 */

public int getGeneratedOLSRPkts() {
    return generatedOLSRPkts;
}

/**
 * The Getter method  for the total number of MAC
 * layer packets
 * @return the total number of AODV data packets generated
 * by all nodes
 */

public int getGeneratedMACPkts() {
    return generatedMACPkts;
}

/**
 * The Getter method  for the total number of drop
 * data packets by all nodes
 * @return the total number of drop data packets by all nodes
 */
public int getDroppedPkts() {
    return droppedPkts;
}

/**
 * The Getter method  for the total number of forwarded
 * data packets by all nodes
 * @return the total number of forwarded data packets by
 * all nodes
 */
public int getFrwPkts() {
    return frwPkts;
}

public double getBytesSent() {
    return bytesSent;
}

public double getBytesReceived() {
    return bytesReceived;
}

/**
 * The Getter method for the send data packet list
 * @return the list of the send data packets
 */
public List getSentList() {
    return this.sentPktList;
}
```

```
    /**
     * The Getter method for the received data packet list
     * @return the list of the received data packets
     */
    public List getRcvList() {
        return this.rcvPktList;
    }

    /**
     * The Getter method for the number of items in the
     * send packet list
     * @return the number of items in the list
     */

    public int countItemsinSentList() {
        int count = sentPktList.getItemCount();
        return count;
    }

    /**
     * The Getter method for the number of items in the
     * received packet list
     * @return the number of items in the list
     */
    public int countItemsinRcvList() {
        int count = rcvPktList.getItemCount();
        return count;
    }

    public void printFileHeader() {
        System.out.println(strBuilder.toString());

    }

//---------------------------------------------------------------
//                           Private Methods
//---------------------------------------------------------------

    /**
     * This method analyzes the ns2 trace file and adds
     * the results found in the trace file to received
     * packets list and sent packets list. It also
     * analyzes the events in the trace file at the AGT,
     * network and MAC layers.
     */
    private void readData() {
        String line = "";
        int sentRouteAODV_REQUEST = 0;
        int sentRouteAODV_REPLY = 0;
        int sentRouteAODV_ERROR = 0;
        int sentRouteDSR = 0;
        int generatedARPPkts = 0;
        int generatedCTSPkts = 0;
        int generatedRTSPkts = 0;
        int generatedACKPkts = 0;
        int countLines = 0;
//open and read the trace file
```

```
              try {
                  trFile.open();
                  while (true) {
                      line = trFile.readNext();
                      countLines++;
                      if (line.equals("")) {
                          break;
                      } else if (countLines < 4) {
                          strBuilder.append(line + "\n");
                      } else if (line.charAt(0) == 's') {
                          if (agentType(line).equals("AGT")) {
                              // count sent packets
                              sentPkts++;
                              StringTokenizer tokens = new
StringTokenizer(line);
                              processSentPkts(tokens);
                          }
                          if (agentType(line).equals("RTR")) {
                    // count AODV routing packets sent by the nodes
                              pat = Pattern.compile("AODV");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  pat = Pattern.compile("REQUEST");
                                  mat = pat.matcher(line);
                                  if (mat.find() == true) {
                                      sentRouteAODV_REQUEST++;
                                  }
                                  pat = Pattern.compile("REPLY");
                                  mat = pat.matcher(line);
                                  if (mat.find() == true) {
                                      sentRouteAODV_REPLY++;
                                  }
                                  pat = Pattern.compile("ERROR");
                                  mat = pat.matcher(line);
                                  if (mat.find() == true) {
                                      sentRouteAODV_ERROR++;
                                  }
                              }
                  // count DSR routing packets sent by the nodes
                              pat = Pattern.compile("DSR");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  sentRouteDSR++;
                                //  System.out.println(line);
                              }
                  // count OLSR routing packets sent by the nodes
                              pat = Pattern.compile("OLSR");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                              //   System.out.println(line);
                                  generatedOLSRPkts++;
                              }
                          }
                  // count all the packtes ARP, CTS,RTS,ACK sent by MAC
                          if (agentType(line).equals("MAC")) {
                              pat = Pattern.compile("ARP");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  generatedARPPkts++;
                              }
                              pat = Pattern.compile("CTS");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  generatedCTSPkts++;
                              }
                              pat = Pattern.compile("RTS");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  generatedRTSPkts++;
                              }
                              pat = Pattern.compile("ACK");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  generatedACKPkts++;
                              }
                          }

                      } else if (line.charAt(0) == 'r') {

                          if (agentType(line).equals("AGT")) {
                              rcvPkts++;
                              StringTokenizer tokens = new
StringTokenizer(line);
                              processRcvPkts(tokens);
                          }
                      } else if (line.charAt(0) == 'D') {
                          // count all dropped packets

                          if (agentType(line).equals("RTR")) {
                              pat = Pattern.compile("cbr");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                              //       System.out.println(line);
                                  droppedPkts++;
                              }
                          } // test to see cbr drop at the MAC level
                          if (agentType(line).equals("MAC")) {
                              pat = Pattern.compile("cbr");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                            //         System.out.println(line);
                                  droppedPkts++;
                              }
                          }
                      }
              //count Forwarded Data Packets by intermediate nodes
                      else if (line.charAt(0) == 'f') {
                         // System.out.println(line);
                          if (agentType(line).equals("RTR")) {
                              pat = Pattern.compile("cbr");
                              mat = pat.matcher(line);
                              if (mat.find() == true) {
                                  //    System.out.println(line);
                                  frwPkts++;
                              }
                          }
                      }
                  }
              } catch (IOException e) {

                  System.out.println("Error reding input");
              }
              generatedMACPkts = generatedARPPkts + generatedCTSPkts +
                                 generatedRTSPkts + generatedACKPkts;
              generatedAODVPkts = sentRouteAODV_REQUEST +
sentRouteAODV_REPLY +
                                  sentRouteAODV_ERROR;
              generatedDSRkts = sentRouteDSR;

          }

          /**
           * agentType
           * @param str String, the line of the trace file for
           * further analysis
           * @return String, the name of the agent (AGT,RTR,MAC)
           */
          private String agentType(String str) {
              agent = DEFAULT_AGENT;
              pat = Pattern.compile("AGT");
              mat = pat.matcher(str);
              if (mat.find() == true) {
                  agent = "AGT";
              }

              pat = Pattern.compile("RTR");
              mat = pat.matcher(str);
              if (mat.find() == true) {
                  agent = "RTR";
              }
              pat = Pattern.compile("MAC");
              mat = pat.matcher(str);
              if (mat.find() == true) {
                  agent = "MAC";
              }
              return agent;
          }

        /**
           * This method takes a line of the ns2 trace file in tokens
           * and add the values time and cbr sequence number into
           * the Received packet List.
           * @param tokens StringTokenizer, the line of the ns2
           * trace file in tokens
           */
          private void processRcvPkts(StringTokenizer tokens) {
              int size = tokens.countTokens();
              String rcvInfo[] = new String[size];
              for (int i = 0; i < size; i++) {
                  //System.out.println(tokens.nextToken());
```

```
            rcvInfo[i] = tokens.nextToken();
        }
        // get the sequence number of the received packet
        rcvPktList.add(rcvInfo[1]);
        rcvPktList.add(rcvInfo[5]);
        bytesReceived+=Double.parseDouble(rcvInfo[7]);
    }

    /**
     * This method takes a line of the ns2 trace file in tokens
     * and adds the values time and cbr sequence number into
     * the Sent packet List.
     * @param tokens StringTokenizer, the line of the ns2
     * trace file in tokens
     */

    private void processSentPkts(StringTokenizer tokens) {
        int size = tokens.countTokens();
        // System.out.println(size);
        //   System.out.println(count_sent);

        String sentInfo[] = new String[size];
        for (int i = 0; i < size; i++) {
            //System.out.println(tokens.nextToken());
            sentInfo[i] = tokens.nextToken();
        }
        // get the sequence number of the sent packet
        sentPktList.add(sentInfo[1]);
        sentPktList.add(sentInfo[5]);
        bytesSent+=Double.parseDouble(sentInfo[7]);
    }

    /**
     * jbInit
     *
     * @throws Exception
     */
    private void jbInit() throws Exception {
    }


} // end of class FileAnalyzer
```

D. CLASS PROCESS DATA

```
package traceanalyzer;


import java.awt.List;

/**
 * The class to calculate the results given by the FileAnalyzer
 * class
 */

class ProcessData {
```

```
//---------------------------------------------------------------
//                          Data Members
//---------------------------------------------------------------

     /**
     * The object of the FileAnalyzer class to provide the
     * results of the trace file
     */
    FileAnalyzer fileAnalyzer;

    /**
     * The packet Delivery Ratio that is (Received data
     * packets/sent data
     * packets) * 100
     */
    private double PDR;

    /**
     * The position in the delayArray to add a new value
     */
    private int index;

    /**
     * An Array to keep the values of the simulation delay
     */
    private double[] delayArray;

    /**
     * The total number of sent data packets by all nodes
     */
    private double sentPkts;

    /**
     * The total number of received data packets by all nodes
     */
    private double rcvPkts;

//---------------------------------------------------------------
//                           Constructor
//---------------------------------------------------------------
    /**
     * The constructor of this class.
     */
    public ProcessData() {
        fileAnalyzer = new FileAnalyzer();
        sentPkts = 0.0;
        rcvPkts = 0.0;
        PDR = 0.0;
        index = 0;
    }
```

```
   //----------------------------------------------------------------
   //                           Public Methods
   //----------------------------------------------------------------

     /**
      * This is the top level method of the class. It calls all
      * other private methods
      */
     public void process() {
       fileAnalyzer.analyze();
       int size = fileAnalyzer.getRcvPkts();
       delayArray = new double[size];
       PDR();
       calculateDelay();
     }
     /**
      * The method to print out the simulation results
      */
     public void printSimulationStats() {
       fileAnalyzer.printFileHeader();
       System.out.println("Sent Data Packets = " + sentPkts);
       System.out.println("Receive Data Packets = " + rcvPkts);
       double dropPkts = (double) fileAnalyzer.getDroppedPkts();
       int frwPkts = fileAnalyzer.getFrwPkts();
       System.out.println("Forward Data Packets = " + frwPkts);
       System.out.println("Drop Data Packets = " + dropPkts);
       System.out.println(
           "Data Packet Delivery Ratio (Received Pkts/Send
Pkts) = " + PDR + " %");
       int AODVPkts = fileAnalyzer.getGeneratedAODVPkts();
       int OLSRPkts = fileAnalyzer.getGeneratedOLSRPkts();
       int DSRPkts = fileAnalyzer.getGeneratedDSRkts();
       int MACPkts = fileAnalyzer.getGeneratedMACPkts();
       int totalRoutingPackets = (AODVPkts + OLSRPkts +
DSRPkts);
       double normalizedRoutingLoad = totalRoutingPackets /
rcvPkts;
       int totalRoutingAndMACPkts = AODVPkts + OLSRPkts +
DSRPkts + MACPkts;
       double normalizedMACload = totalRoutingAndMACPkts /
rcvPkts;
       System.out.println("AODV Routing Packets = " + AODVPkts);
       System.out.println("OLSR Routing Packets = " + OLSRPkts);
       System.out.println("DSR Routing Packets = " + DSRPkts);
       System.out.println("MAC Packets (ARP, ACK, CTS, RTS) = "
+ MACPkts);
       System.out.println("Normalized Routing Load = " +
normalizedRoutingLoad);
       System.out.println("Normalized MAC load = " +
normalizedMACload);
       End2EndDelayStatistics();
       System.out.println("Bytes sent = "+
fileAnalyzer.getBytesSent());
       System.out.println("Bytes received = "+
fileAnalyzer.getBytesReceived());

     }
```

```
      //---------------------------------------------------------------
      //                           Private Methods
      //---------------------------------------------------------------

          /**
           * The method to calculate the packet delivery ratio
           */
          private void PDR() {
              sentPkts = (double) fileAnalyzer.getSentPkts();
              rcvPkts = (double) fileAnalyzer.getRcvPkts();
              PDR = (rcvPkts / sentPkts) * 100;

          }

          /**
           * The method to calculate the delay between the time the
           * data packet send by the originator node and the time the
           * data packet received by the destination node. It writes
           * the result in an Array. The total number of received data
           * packets defines the size of the Array
           */
          private void calculateDelay() {
              List sentList = new List();
              List rcvList = new List();
              sentList = fileAnalyzer.getSentList();
              rcvList = fileAnalyzer.getRcvList();
              double sentTime = 0;
              double rcvTime = 0;
              double delay = 0;
              int sentPktListSize = sentList.getItemCount();
              int rcvPktListSize = rcvList.getItemCount();
              for (int i = 0; i < sentPktListSize; i++) {
                  sentTime = Double.parseDouble(sentList.getItem(i));
                  i++;
                  int sent_pkt_sequence_number =
Integer.parseInt(sentList.getItem(i));
                  for (int j = 1; j < rcvPktListSize; j++) {
                      int rcv_pkt_sequence_number =
Integer.parseInt(rcvList.getItem(j));
                      if (sent_pkt_sequence_number ==
rcv_pkt_sequence_number) {
                          rcvTime =
Double.parseDouble(rcvList.getItem(j - 1));
                          delay = rcvTime - sentTime;
                          addDelay(delay);
                      }
                      j++;
                  }
              }
          }
          /**
           * This method adds an element in the Array
           * @param delay the time the data packet received by the
           * destination node minus the time the data packet sent by
           * the originator node
           */
          private void addDelay(double delay) {
              delayArray[index] = delay;
              index++;
          }

          /**
           * This method calculates the minimun, the maximun and the
           * average delays
           */
          private void End2EndDelayStatistics() {
              double min = delayArray[0];
              for (int i = 1; i < delayArray.length; i++) {
                  if (delayArray[i] < min) {
                      min = delayArray[i];
                  }
              }
              System.out.println("Minimun End2End Delay = " + min *
1000 + " milis");
              double max = delayArray[0];
              for (int i = 1; i < delayArray.length; i++) {
                  if (delayArray[i] > max) {
                      max = delayArray[i];
                  }
              }
              System.out.println("Maximun End2End Delay = " + max *
1000 + " milis");
              double sum = 0;
              double averageDelay = 0;
              for (int i = 0; i < delayArray.length; i++) {
                  sum += delayArray[i];
              }
              averageDelay = sum / delayArray.length;
              System.out.println("Average End2End Delay = " +
averageDelay * 1000 + " milis");
          }

          /**
           * The Getter method for all sent data packets by the nodes
           * @return double, the number of all sent data packets.
           */
          public double getSentPkts() {
              return sentPkts;
          }

          /**
           * The Getter method for all received data packets by the
           * nodes
           * @return double, the number of all received data packets by
           * the nodes
           */
          public double getRcvPkts() {
```

```
        return rcvPkts;
    }

    /**
     * The Getter method for packet delivery Ratio
     * @return double, the packet delivery ratio (PDR)
     */
    public double getPDR() {
        return PDR;
    }
}
```

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